

LATE HOLOCENE ENVIRONMENTS ON THE
NORTHERN PERIPHERY OF THE GREAT BASIN

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PROLOGUE AND PREVIEW

Ice Age Climate and Vegetation

No vegetation on earth escaped the repeated stress of glacial climates and interglacial adjustments. With each glacial cycle species displaced by climate, ice, water and competition responded through growth form, migration or selection, or faced local extinction. At varying paces in different places (Wright 1984) species repeatedly abandoned then reclaimed the same terrain, but not always with the same associates.

The grip of glacial climate squeezed North Africa dry, allowing cold winds to heap-up Saharan sands and sweep dust clouds far out to sea (Kutzbach 1980; Nicholson & Flohn 1980). It brought polar desert and steppe to Europe, coniferous forests to the eastern U.S. (Davis M. B. 1983), and snow-capped mountains, pluvial lakes and pygmy woodlands to North American deserts (Spaulding et al. 1983; Betancourt 1987). Savannah spread in the New World tropics.

With Holocene warming temperate deciduous forests regained dominance in Europe and the eastern U.S. Early Holocene monsoons nourished deflation basins, shrubby steppe and Neolithic pastoralists, then retreated to the Sahara's southern fringe (Haynes 1987). Western America's pluvial lakes rapidly shrank to ephemeral playas and woodlands abandoned our deserts (Mehring 1986). Savannah gave way to shrubs and trees in tropical South America (Leyden 1985).

In contrast with the southern Plains, Southwest, Colorado Plateaus and eastern Great Basin, where woodland and forest expanded during colder times, sagebrush steppe prevailed in the interior northwestern U.S. while forests and woodlands dwindled (Mehring 1985, 1986). For example, in the Columbia Basin, Washington, sagebrush and grass pollen dominated for most of the last

33,000 years; here periglacial steppe accompanied growth of mountain ice caps and glaciers (Barnosky 1984, 1985). Elsewhere along the unglaciated western edge of the Rockies and across the Snake River Plain sagebrush steppe persisted through the last 70,000 years and more. Dwarf prostrate junipers (Juniperus communis, J. horizontalis) in Pleistocene woodrat middens from southeastern Oregon led Wells (1983) to envision a full-glacial subarctic landscape fringing the northern Great Basin. His suggestion finds support in pollen records from Steens Mountain, Oregon, where sagebrush-dominated steppe followed retreating glaciers up the mountain; it has persisted in a broad band without coniferous trees to the present day.

Though dearth and uneven distribution of dated fossil records still leaves much to imagination, the lengthening list of pollen and plant macrofossil studies continually constricts bounds of reasonable conjecture.

The major events of Pleistocene vegetation of the northern Great Basin especially southeastern Oregon and adjacent areas can be considered in four chronological periods representing certain broad climatic episodes of which only the last 2000 to 4000 years are the primary object of this report.

These periods and their characteristics are:

1. Interstadial assemblages show a degree of variation expectable during the late glacial and Holocene, and have potential, if superficial, counterparts in modern vegetation.
2. Full glacial (24,000-12,500 B.P.) and late glacial (12,500-10,000 B.P.) assemblages show maximum vegetational displacement and rapid response to initial warming, wasting glaciers and shrinking lakes.
3. Holocene assemblages reflect halting vegetational adjustments to rapid post glacial warming, followed by cooling (apparent by 5400 B.P.), and punctuated by brief, but clear responses to short sharp climatic episodes.

4. Of all Quaternary vegetation changes, the most distinctive and perhaps long-lasting has come to eastern Oregon only recently with the cow, plow, axe, and alien weeds. Human influence on this area, however, especially through burning goes back at least another 11,500 years.

Present vegetation of the northern Great Basin represents a passing phase of species adjustments during a part of the present interstadial--the Holocene. These changes of the last 10,000 years have been influenced by climate, dispersal potential, competition, selection, soil development, topography, volcanic eruptions, fire, man and chance.

Holocene Events of the Steens Mountain Area

The major recognized paleoecological events that followed retreat of the Steens Mountain ice cap are briefly summarized chronologically. These come from both recently published studies (Mehringer 1985, 1986; Mehringer and Wigand 1987, 1988; Wigand 1987), and those to be reported herein:

1. Fish Lake on Steen Mountain was ice-free by 12,500 B.P. Sagebrush, grass and juniper (probably J. communis) pollen characterize its late glacial assemblage.
2. By about 9500 B.P. Wildhorse Cirque was ice-free and algae remains from Fish Lake began to increase. The pattern of sagebrush and grass pollen dominance, that has characterized both sites to the present time, was well established.
3. As measured by relatively large sagebrush/grass ratios (more sagebrush in relation to grass) the period from about 8700 to 5400 B.P., though variable, was a time of relatively deficient effective moisture at Fish Lake.

4. The same variation in fossil pollen at Wildhorse Lake, at the current upper elevational limit of sagebrush, suggests periodic upward advance of sagebrush owing to warmer episodes with fewer snow patches lasting into summer (about 7000 to 3600 B.P.). But, overall the sequence from Wildhorse Lake atop Steens Mountain suggests--by synthesizing the pollen rain of desert valleys below--a regional trend toward an expanding lower sagebrush zone since 8000 B.P.; the Diamond Pond pollen record exhibits the same feature over the last 5500 years.
5. A sharp, short-lived shift to more effective moisture followed two eruptions of Mount Mazama (Crater Lake, Oregon) that left tephra layers in Fish and Wildhorse lakes about 6800 B.P.
6. Another nearby eruption from an undetermined source spread pumice over Steens Mountain about 5460 B.P. This date also marks the beginning of a general shift toward increasing grass importance at Fish Lake and sagebrush abundance at Diamond Pond. Three more tephtras from Cascade vents fell on Steens Mountain about 2845, 1325 and 1140 B.P. In all six dated volcanic ashes allow precise correlation of late Holocene deposits.
7. Fossil pollen frequencies from all sites reflect extreme drought about A.D. 1500; otherwise, events of the late Holocene are best seen at Diamond Craters. The Diamond Pond record starts about 6000 B.P. with greasewood and saltbush pollen dominance, and ephemeral ponds with the water table 17 meters below today's.
8. Plant macrofossils and pollen indicate a shift toward perennial ponds and sagebrush importance about 5400 B.P.
9. From shortly after 4000 B.P. to nearly 2000 B.P. grass and juniper pollen, together with abundant charcoal, reflect episodes of juniper

grasslands with different fuel and fire regimes than before or since. Macrofossils from nearby radiocarbon dated woodrat middens confirm juniper's expanded presence. According to macrofossils of aquatic plants, Diamond Pond was at its deepest during this period; however, its depth varied considerably. Both water levels and percent juniper pollen fell dramatically with a sharp drought about 2900 B.P. About 2200 B.P. sagebrush reclaimed importance from juniper and grass.

10. Environmental shifts of the last 2000 years are only discernable through the close interval analyses reported herein. Most importantly for these studies, the new analyses of pollen and woodrat middens confirm the dynamic nature of eastern Oregon's steppe over the last few hundred years as well as longer trends in vegetation change extending over several hundreds or thousands of years. They also indicate that--as measured by charcoal abundance, fossil pollen and macrofossils--artificially induced fire regimes and shrub abundance of today have near analogs in the recent prehistoric past.

Management Implications

When considering vegetation history the past is the key to the present and, in historical perspective, change is inevitable. These studies are a step toward defining what is natural, and the magnitude and chronology of decade, century or millennia-long changes in eastern Oregon's steppe and woodland on a scale permitting comparisons with historic events. These fossil records give new information on prehistoric climate and vegetation that should enhance accurate estimates of natural conditions upon which management is generally based. When viewed over the last 500 years, some differences of the last 100 years, such as the success of juniper, will seem less remarkable than before. Others, like increasing sagebrush at lower elevations may appear as

temporary ripples on a rising wave rolling on from the mid-Holocene towards the returning ice age.

When did they live here and how did they make their living? These are among the simplest questions considered by cultural resource managers. Yet, without these understandings grander questions may not be answerable. Some of the simplest to the most complex notions about northern Great Basin archaeological remains are testable only with knowledge of the chronology of past environments. Having this information does not assure understanding; lack of it most assuredly limits understanding. With this report the most detailed environmental chronology for the Holocene of the northern Great Basin awaits cultural resource managers queries.

Studying natural and cultural resources on public lands can be a first step toward sharing information gained with the public. The data presented here can be incorporated easily in interpretive programs. For example, in addition to information on vegetation and fire, cores from Steens Mountain lakes hold the history of deglaciation, the intensity and direction of the earth's magnetic field over the last 10,000 years, and a dated record of Holocene volcanic ashes that fell there. There are also many simply illustrated examples of coring, dating and other methods devised to obtain secrets of the past from yesterday's mud.

INTRODUCTION

Information on Great Basin rangeland ecosystems and the roles of environmental factors, such as climate and fire, in these systems usually are based on studies of a few decades at most. Until now it was not known if change wrought by livestock or fire suppression in eastern Oregon over the last 100 years was any more dramatic than "natural" variation over the past few hundreds or thousands of years. Management responses to juniper expansion, sagebrush abundance and fire continue to fan flames of controversy fueled by opposing perceptions of the pristine state in steppe primeval. But, late-Holocene fossils from lake sediments and woodrat middens offer answers to questions about the rate and magnitude of prehistoric variation in northern Great Basin steppe and woodland.

Recent studies in eastern Oregon indicate punctuated differences in importance of juniper, grass, sagebrush and charcoal. Dynamic patterns of species responses to climate--as tempered by dispersal potential, competition and chance--seem apparent on scales of centuries and millennia (Mehring and Wigand 1987). For example, radiocarbon dated pollen records from Diamond Pond, supported by macrofossils from woodrat middens, disclose juniper's apparent rapid responses to climatic events. At Fish and Wildhorse lakes on Steens Mountain, pollen ratios indicate the changing abundance of grass and sagebrush (Mehring 1985, figure 12). Counts of microscopic charcoal fragments attest to climatic regimes producing many fires to few fires with occasional conflagrations.

Though these findings seemed evident when averaged over several decades and centuries, I wished to more clearly relate them to questions of range and cultural resource management, and to facilitate their use in interpretative programs. It was necessary, therefore, to improve temporal resolution by

decreasing sample intervals to potentially compare fossil sequences with short lived, but ecologically significant climatic events such as the droughts of the 1920s and 1930s. Also, time within or between samples would ideally represent less time than one generation of the organism(s) being studied.

Though western juniper (Juniperus occidentalis), for example, may flower by 25 years of age it does not approach its potential for pollen production for another 50 years or more (L. E. Eddleman, personal communication). Nonetheless, history of western juniper would be best resolved by a fossil pollen sequence with samples spaced no more than 25 years apart. Perhaps less than 20 years, the span of a single generation, should separate samples used to evaluate potential human responses to varying environments in the northern Great Basin. When considering people, however, these relationships are not so simple. Human resource managers have affected the state of steppe and woodland on this continent for at least 12,000 years. They diverted water, accidentally and intentionally spread propagules, and otherwise modified local habitats to their liking (Downs 1966; Lawton et al. 1976). Because burning was their most important means of manipulating the environment (Barrett and Arno 1982; Gruell 1985), prehistoric fire regimes must have varied with population densities and lifeways. In any case, details that could only be revealed by close interval sampling were prime objectives of these studies.

Research reported herein is built upon paleoecological records spanning the last 13,000 years. These investigations, begun in the mid 1970s as a part of the Steens Mountain Prehistory Project, are partially presented in (Aikens, Grayson and Mehringer 1982; Mehringer 1985, 1986; Mehringer and Wigand 1986, 1987, 1988; Verosub and Mehringer 1984; Verosub et al. 1986; Wigand, 1987). They include radiocarbon, tephra and paleomagnetic dating, studies of fossil pollen, algae and plant macrofossils, textural analyses of lake sediments, and

the stratigraphy and chronology of desert dunes. In addition to Diamond Craters, areas of concerted study have included Fish and Wildhorse lakes on Steens Mountain, and dunes in Catlow and Alvord valleys (Figure 1).

In this report I describe:

1. plant macrofossils recovered from 24 woodrat middens from the Bureau of Land Management Outstanding Natural Area, Diamond Craters, Oregon,
2. pollen content of 12 of the Diamond Craters middens and another two from the Catlow Rim, and
3. pollen, algae and microscopic charcoal fragments from close interval analyses of the last 1500-2000 years of cores from Diamond Pond and Fish Lake.

The paleoclimatic and chronological significance of western juniper remains from the Diamond Craters woodrat middens are considered by comparing their age distributions with continuous juniper pollen records from nearby Diamond Pond (Malheur Maar). New close interval analyses of pollen samples spanning the last 2000 years provide a basis for understanding the significance of macrofossil assemblages from woodrat middens as compared with pollen records of the past 5000 years. Lastly, complimentary evidence of past environments from lake cores and from woodrat middens lend greater resolution to vegetation history than either alone.

These midden and pollen analyses represent twice the number reported previously (Mehring and Wigand 1987). This additional information has furthered understanding of past vegetational responses to climatic variability, particularly over the last 500 years. The combination of juniper pollen from a closely sampled core and radiocarbon dated juniper macrofossils from nearby woodrat middens gives a better notion of western juniper's history and the relative significance of its recent success (Burkhardt and Tisdale 1976).

In addition to the main focus at Diamond Craters and Fish Lake, we collected cores from Blue Lake, BLM Wilderness Area, Pine Forest Range, Nevada, and Upper Cow Lake, Jordan Craters BLM Research Natural Area, Oregon (Appendix A). Additional woodrat middens collected along the Catlow Rim could not be analyzed within the constraints of this project, but two were radiocarbon dated. The initial contribution of these BLM-supported studies (Mehring and Wigand 1987) is attached. Wigand's (1987) paper on Diamond Pond (prepared while he was partially supported by this project as a post-doctoral research associate) is in press, in Great Basin Naturalist; a single copy accompanies the original of this report.

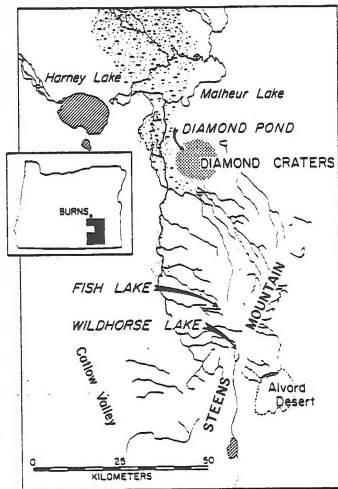


Figure 1. Map of the study area in southeastern Oregon.

METHODS

Multiple, overlapping 10-centimeter diameter cores of lake sediment were collected in plastic core barrels from near the center and deepest areas of Fish Lake (9.3 m) and Diamond Pond (2.0 m) in 1978 and 1979 (Figures 2, 3.) They have been maintained in cold storage at Washington State University. Because core barrels were measured and marked, and the sediments were also marked, when initially logged and sampled, we could accurately remove another 150 samples from deposits spanning the last 2000 years. One hundred new analyses were completed for the last 2000 years at Diamond Pond and 57 were added to the data set of the last 1500 years at Fish Lake. For these studies it was necessary to extend close interval sampling through the historic period.

Because sediments near the mud-water interface are easily disturbed by coring, 30 to 40-centimeter deep sections were frozen in place with a "box-freezer" that utilizes dry ice and alcohol (Huttun and Merilainen 1978; O'Sullivan 1983). These sections, collected on November 7 and 8 after sagebrush had flowered and lakes had undergone fall turnover, extended the pollen, charcoal and algae records through 1985. The frozen sections of loose lake bottom were correlated with the uppermost cores by distinctive stratigraphic marker beds and verified by overlapping pollen spectra. As a result, 12 cm of loose lake bottom deposited in the last 20 years or so were added to the top of the Diamond Pond section, whereas 3 cm representing about 10 years were added to the Fish Lake section.

To conform with the height of all other samples, the frozen slabs were cut on a band-saw into 1-cm tall strips whose volume was determined (after the samples melted) by centrifuging them in graduated 10 ml tubes for 1 minute at 1000 RPM. This compacted sediment volume more closely approximates down-core

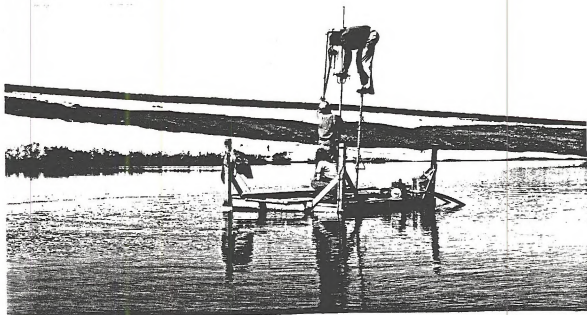


Figure 2. Coring Fish Lake (June 20, 1979).

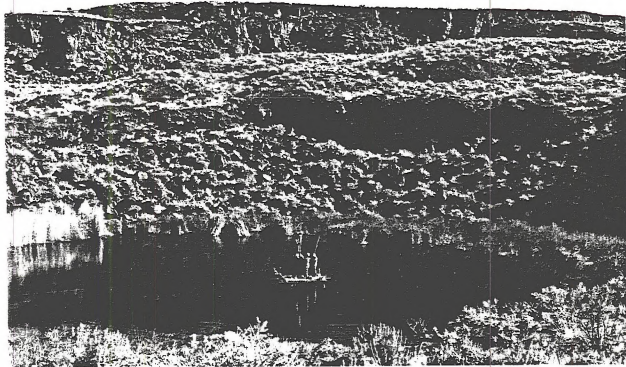


Figure 3. Washington State University students coring Diamond Pond (October, 1978). One of the many explosion craters in this volcanic terrane (Malheur Maar) holds a 50-meter diameter pond that has accumulated pollen, algae, seeds and molluscs for at least 6000 years. Fringed by cat-tail and bulrush, Diamond Pond lies astride the sagebrush-shadscale ecotone.

sediment samples used for pollen analyses and weight loss on ignition (Dean 1974). Both volume and dry weight were measured for all samples. Lycopodium spore tracers, introduced as the first step in pollen extraction, facilitated estimates of pollen, algae and microscopic charcoal fragments.

Fire history is important in evaluating interactions of climate and vegetation, and past human influence in shaping the environment. Charcoal preserved in lake sediments and soils may give indications of past fire frequency or intensity (Patterson et al. 1987). In any particular case, size and numbers of microscopic particles preserved in lake cores might reflect the fuel that was burned, or the size, intensity or distance to the fire. While counting pollen samples we recorded all charcoal fragments >25 μm in three size classes (25-50, 50-100 and >100 μm). Because the three sizes were highly correlated ($P > 0.001$) they were summed in a single category.

Even though annual variation may be large, pollen is produced within predictable limits, whereas charcoal is produced occasionally in great abundance that varies with vegetation type. Years contained in samples from cores vary so that counts of microscopic charcoal may represent single or repeated fires, and charcoal recirculated by wind and mixed in lake sediments following a fire. Therefore, I have used the charcoal/terrestrial pollen ratio as an indicator of past fire regimes. This ratio reflects the balance between annually and sporadically produced wind born particles. The method is far from precise; still, regional patterns of fire history may emerge from studies of charcoal accumulation in lake sediments (Mehring 1985, table 3; Tolonen 1983).

Age of lake cores was determined from 38 radiocarbon dates from three sites (Diamond Pond, and Fish and Wildhorse lakes on Steens Mountain) that are correlated by tephra. At Diamond Pond and Fish Lake Cesium-137 abundance

indicated approximate positions of samples dating from A.D. 1945 and 1964; though preliminary, these estimates are most probably accurate to within a decade. Four scales--as befits the topic--are used in presenting pollen data.

I used depth and radiocarbon years B.P. where years between events are not of primary importance or for comparing other data so treated. Tree ring corrected radiocarbon ages B.P. and tree ring corrected years A.D./B.C. enhanced comparisons with tree ring records and estimates of years within or between samples; for example, in estimating pollen or charcoal accumulation rates. Calendar corrections for core ages were determined by converting radiocarbon dates to tree ring ages (Klein et al. 1982). Core age for any particular level comes from deposition rate derived by curve fitting (4th order polynomials) of radiometric dates or their tree ring corrections. S. W. Robinson's (1986) computer program converted radiocarbon dates of woodrat middens to calendar years.

We prepared woodrat middens by first removing uneven and weathered surfaces with a hammer and chisel. Excepting the very smallest samples, middens were then split along bedding planes to identify and separate distinct stratigraphic units; larger middens were sawed, vertical to their apparent plane of deposition, to better reveal their depositional sequence. The stratigraphically discrete pieces of urine cemented dung and plant remains were then washed thoroughly in hot water and soaked for 10 to 24 hours. The undissolved midden and freed plant remains, dung and sediments were then poured onto nested, stainless steel sieves (8, 10, 24 and 42 mesh) and washed thoroughly. This process was repeated until midden contents no longer adhered and were free of amberat (usually 3 to 5 days).

Pollen samples were taken from middens during the soaking and sieving process. After a sample of consolidated midden was reduced by at least one-

half and washed, it was placed in distilled water for several hours. The sample was again poured onto the nested screens and washed with distilled water; everything passing the 42-mesh screen was retained, mixed, and about 200 ml were poured through a 100 mesh screen into a 250 ml beaker. Lycopodium spore tracers were added as a check on extraction. The sample was then concentrated by centrifuging in 50 ml tubes, extracted using routine hydrofluoric acid and acetylation methods, stained, and mounted in silicon oil.

After drying and sorting we identified plant remains by comparison with our collections and those of the Marion Ownbey Herbarium, Washington State University. They were counted, dried at 40°C, cooled in a desiccator, and weighed to five places, rounded to three; .001 grams indicates a trace that may weigh less (Table 1). Abundance, state of preservation, and usefulness of the parts preserved for distinguishing particular taxa determined levels of identification. Identifications of some grasses and composites required special expertise beyond our competence that was provided by Paul M. Peterson and Joy Mastrogriuseppe of the Marion Ownbey Herbarium.

THE WOODRAT MIDDENS

After preparing the initial report for this BLM-supported project (Mehring and Wigand 1987) we collected 12 more middens from Diamond Craters and continued with identification of undetermined macrofossil remains from all Diamond Craters middens. Here I report all 24 middens with 25 additional taxa. Middens were collected from Diamond Craters without regard to their apparent age or content. The few not taken were left only because they occupied inaccessible deep crevices or high ledges. I estimate that--following clues from topographic maps, air photos, and informants--we investigated at least 70 percent of the Diamond Craters terrane most likely to

Table 1. Macrofossils from woodrat middens, BLM Outstanding Natural Area,
Diamond Craters, Oregon. (see enclosure)

hold ancient middens (Figure 4). Most potential sites are too moist for preservation of middens. In fact, this midden series includes fist-size midden remnants, and lumps of amberat with no exposed fossil plants. The ten (unstudied) middens collected from Catlow Valley represent only a small sample of those located and they are large by comparison. Midden contents are arranged in Table 1 by site, area and age. Radiocarbon dates are presented in Table 2.

Table 2. Radiocarbon dates and tree ring corrected radiocarbon ages from woodrat middens from Diamond Craters and the Catlow Rim, southeastern Oregon.

Laboratory Number	Radiocarbon Date (B.P.)	Tree ring Corrected Age (A.D./B.C.)	Site	Material Dated	Elevation (Meters)	Slope Direction
Diamond Craters						
WSU-2725	835+ 55	1200+ 60	GD-2	Juniper	1410	ENE
*WSU-3479	1055+130	975+130	GO-11	Dung	1400	WSW
*WSU-3584	1140+120	890+125	GD-11	Juniper	1400	WSW
WSU-3484	1540+130	510+130	GD-7	Juniper	1395	NNE
WSU-3478	1560+ 60	500+ 75	GD-9	Juniper	1400	WSW
WSU-2727	1625+150	420+160	GD-3	Juniper	1410	ENE
WSU-3480	1700+ 90	335+110	GD-13	Juniper	1400	WSW
WSU-3476	1960+110	50+125 A.D.	GD-4	Dung	1400	WSW
WSU-3485	2210+110	265+145 B.C.	GD-12	Juniper	1400	WSW
WSU-3481	2260+ 80	330+ 95	GD-14	Juniper	1400	WSW
WSU-2575	2340+ 90	420+125	RA-2	Juniper	1330	WNW
WSU-2447	2350+ 80	425+115	SP-1	Juniper	1280	WSW
WSU-3477	2360+ 80	440+120	GO-8	Juniper	1400	WSW
WSU-2726	2390+260	495+330	GD-1	Juniper	1435	WSW
WSU-2572	2455+ 90	590+170	RA-3	Juniper	1330	ENE
WSU-2581	2670+ 70	845+ 50	SP-3	Juniper	1280	WSW
WSU-2574	2680+ 90	855+ 75	SC-4	Juniper	1290	WSW
WSU-2448	2700+ 80	870+ 65	SC-2	Oung	1290	WSW
WSU-2441	2800+110	980+135	SC-1	Juniper	1290	WSW
WSU-2573	3000+ 75	1250+110	RA-1	Juniper	1330	WNW
WSU-3570	3045+120	1305+180	SP-2	Juniper	1280	WSW
WSU-3482	3270+100	1565+115	GD-5	Juniper	1400	WSW
WSU-3483	3380+ 80	1690+100	GD-6	Juniper	1400	WSW
WSU-3475	4075+ 90	2645+135	NC-1	Dung	1295	ESE
Catlow Rim						
WSU-3501	890+ 80	1135+ 90	DC-2	Juniper	1460	SSW
WSU-3500	6100+200	5040+225	TM-1	Dung	1460	WSW

*Two dates from GD-11 averaged as WSU-3484, 1100+90 B.P. (A.D. 935+90).

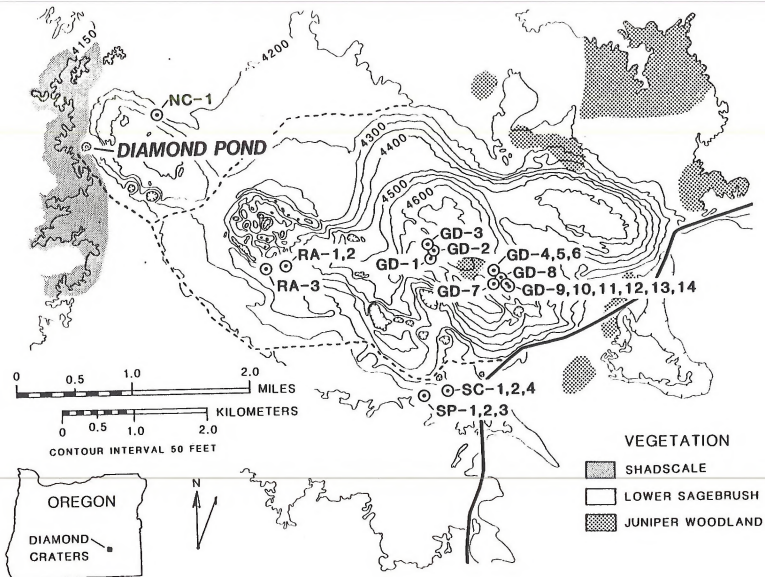


Figure 4. Location of woodrat middens, Diamond Craters, Oregon (Table 1).

Both dung and dust trapped within woodrat middens hold abundant pollen that could include fossil taxa not represented by macrofossils. Also, pollen from middens may give clues to the regional vegetation beyond the small home range of woodrats and it may prove important in evaluating assumptions that woodrat midden macrofossils represent only very local assemblages tied to rimrock and, therefore, less influenced by effects of fire. Table 3 gives pollen and charcoal counts from 14 middens.

Macrofossils from Woodrat Middens

Nomenclature, and identifications follow descriptions and illustrations in Cronquist et al. (1977, 1984) or Hitchcock and Cronquist (1973). Several taxa deserve special comment and some taxonomic revisions may not correspond to common usage. For example, we followed Cronquist et al. (1984) in listing Sandberg's bluegrass as Poa secunda var. sandbergii (Table 1) rather than the familiar Poa sandbergii.

Rabbitbrush has many species, subspecies and hybrids (Anderson 1986a,b). Because its abundant bracts possessed strongly keeled, generally acute, dark-tipped phyllaries, we attributed all rabbitbrush in these middens to Chrysothamnus nauseosus without reference to subspecies. Perhaps expert examination of these fossils would reveal more complexity (Anderson 1980). Likewise, Artemisia spinescens was not observed and, because of taxonomic complexity, all sagebrush remains were referred only to subgenus Tridentatae (McArthur et al. 1979; Shultz 1986). By contrast, size, surface texture and shape of Phacelia seeds permitted their specific identification.

At least four genera of the Boraginaceae and five species of Cryptantha were represented by distinctive seeds (Table 1). The nutlet of Cryptantha pterocarya contains three winged seeds surrounding a central seed lacking wings; we recovered both types. As in Brickellia microphylla, characteristic

twigs, bracts, seeds or leaves often occurred together and in abundance.

Other taxa were determined less assuredly to genera or family, and among the rare macrofossils another dozen, or so, genera remain unidentified.

All middens occur between 2 km and 100 m from the nearest patches of juniper woodland--outside the foraging range of woodrats--and as much as 1 km from the nearest single tree. At Graben Dome some middens (GD-4, 5, 7, 12, 13 and 14) are within 50 m of a standing snag, stump, or young tree (Figures 5, 6). Thus, as a group, the Graben Dome middens require the least change to account for western juniper's presence in fossil middens. The age distribution of all middens suggests a chronological pattern to juniper abundance at sites where juniper is absent today (Figure 7).

Determining a universally applicable method of quantifying plant remains from woodrat middens would be difficult at best. The relative weight of middens from southeastern Oregon is most often determined by their content of cobble to silt sized weathered basalt and wind born dust. Relative abundance of plant remains, dung and amberat influences weight as well. Midden size is subject to the same constraints. The volume (by displacement of water) of midden separated in this study varied from 110 (GD-14) to 1000 cc (GD-7). Larger samples tend to have more plant remains and variety, yet GD-14 is only one-half the size of GD-10 but has greater variety because GD-10 is primarily amberat with few plant remains. In short, to quantify remains based on original sample weight or volume one must first determine the amount of stone, amberat, dust, dung, branches, twigs, etc.--not just a midden or subsample's weight or volume. To allow comparison among these samples we weighed all identified plant remains and counted the seeds and fruits (Table 1).

Western juniper (Juniperus occidentalis) dominates all Diamond Craters middens. Sagebrush is the the most abundant shrub, whereas Indian ricegrass



Figure 5. Basalt rim in the distance held Graben Dome middens (GD-9 to GD-14); note the charred western juniper snag and two young trees on the lower slope (March 14, 1986).

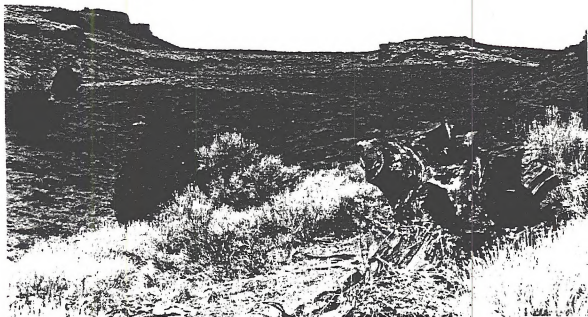


Figure 6. Basalt rim in the distance held Graben Dome middens (GD-2 and GD-3); note the cut stump of western juniper in the right foreground (March 14, 1986).

**Diamond Craters
Woodrat Middens**

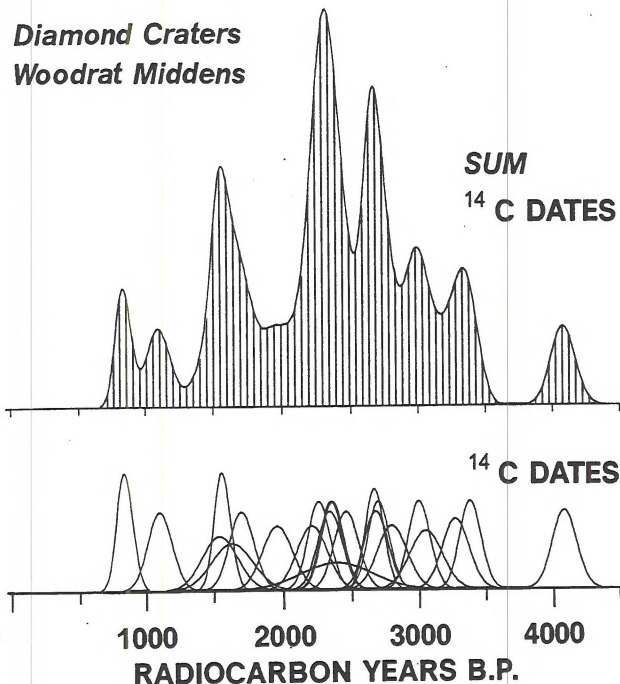


Figure 7. Plots of radiocarbon dates from 23 woodrat middens from Diamond Craters, Oregon (Table 2). Each date is plotted as a normal distribution with a probability of one; width at the base is three standard deviations. Because the areas under all curves are equal, a date with a small standard deviation gives a taller peak than one with a larger standard deviation. Areas under the curves for all dates are summed above in ten year increments (Geyh 1980; Geyh, M. A., and P. de Maret 1982).

(Oryzopsis hymenoides) and squirrel tail (Sitanion hystrix) are paramount among the grasses. Excepting abundance of juniper, the fossil plant assemblages suggest little vegetational change over the last 4000 radiocarbon years. For example, Penstemon deustus is characteristically scattered on Surprise Flow and its remains are most common in Surprise and nearby Spattercone caves. It is otherwise only important in the Graben Dome-6 midden that is adjacent to a basalt flat with patches of thin soil. By contrast, Indian ricegrass is abundant in most Graben Dome middens; it is currently favored there by deeper pumice soils. Ribes aureum occurs only in the 4075 B.P. midden from Nolf Crater. Today, it is common in moist rock rubble on the shaded crater slopes. Seep-weed (Suaeda sp.) was also only recognized in the Nolf Crater midden, but we did not observe it there in 1986.

Fossil Pollen from Woodrat Middens

Cheat grass (Bromus tectorum) is a recent introduction; still, its awns are found deep within cracks in ancient woodrat middens, adhering to sticky amberat, and completely imbedded in hard surface amberat that becomes viscous when moist. Despite removal of outer surfaces and special attention to presence of cheat grass, it was discovered in two samples. If cheat grass can be incorporated in amberat, then it is likely that pollen postdating occupation of a midden has been incorporated in amberat filled cracks and surface amberat over centuries or millennia. Either Neotoma dung or the interior of samples being prepared for macrofossil study might provide samples of pollen for comparison with other midden remains. These would best reflect regional and local wind-born pollen, and pollen that adhered to woodrats and to plants they ate or collected to build the den and nest.

Pollen from the interior of 12 middens from Diamond Craters corresponds to the macrofossils in their monotonous predominance of juniper and sagebrush

pollen (Table 3). Distant conifers, oak and alder contributed to the minimal expected background of such non-local pollen. We anticipated sedge and cat-tail pollen from marshes of the Blitzen Valley, 10 km downwind; Botryococcus suggest recirculation in dust blown from floors of ephemeral ponds and seasonally dry marsh margins. Paucity of Sarcobatus and other chenopod pollen, however, is surprising considering their abundance in Diamond Pond cores of the same age, but in agreement with their rarity as midden macrofossils. Charcoal values of 9.2 to 61% of total pollen reflect differences expected in samples representing few enough years to distinguish nearby fires. They confirm the prehistoric place of fire in steppe.

Other taxa represented by macrofossils are rare or absent as pollen. The 10,941 pollen counted from the Diamond Crater middens included not a single member of the Boraginaceae, so common among the seeds in most samples (Table 1). Likewise, pollen of Leptodactylon, Phacelia, Astragalus, Galium, and Mentzelia, were present but rare. Potential local taxa, not recognized as macrofossils, include Navarretia, Physalis, Delphinium, and three genera of Umbelliferae. These could also have been wind-born long distances along with pollen of Cercocarpus and Ceanothus. By comparison with the macrofossils, pollen from Diamond Craters middens was relatively uninformative. It suggests, however, that in the past sagebrush and juniper were locally dominant and probably regionally abundant.

Pollen of two middens from the lower sagebrush zone below Catlow Rim (eastern margin of Catlow Valley), about 60 kilometers to the south, provide a comparison (Table 3). Though, not studied, cursory examination reveals that one of these contains western juniper (Dry Creek-2; WSU-3501, 890±80 B.P.). The other lacks juniper though western juniper trees are now common there (Three Mile-1; WSU-3500, 6100±200 B.P.; Figure 8).

These two sites reflect contrasting local and regional pollen pictures. Like the Diamond Craters middens, DC-1 is dominated by juniper with sagebrush pollen, whereas TM-1 shows abundant sagebrush pollen and little juniper. The TM-1 midden suggests a sagebrush dominated landscape; pollen of willow, sedge and monkey-flower (Mimulus guttatus), and spores of horsetail (Equisetum) reveal a nearby source along Three Mile Creek.



Figure 8. One of the woodrat middens from this site on the Catlow Rim at Three Mile Creek dates to 6100 B.P. Though juniper is common here today the midden lacks juniper macrofossils and contains only 1.2% juniper pollen (Table 3; March 10, 1986).

THE LAKE CORES

As with the woodrat middens, pollen analyses of lake cores are twice the number reported previously. The sum of terrestrial pollen--that averaged 757 grains for 197 Diamond Pond analyses and 744 for 179 Fish Lake samples--

excludes plants whose major abundances at these sites occur in or around aquatic habitats (e.g., sedges, cat-tails, pondweeds), spores (e.g., ferns and quillwort), nor acid resistant algae (e.g., Pediastrum, Tetradron and Botryococcus,) which are many times more abundant than pollen. On the average, at Fish Lake, 448 Lycopodium tracers and 99 charcoal fragments were recorded while counting the 744 terrestrial pollen. At Diamond Pond, on the average, 638 Lycopodium tracers and 1453 charcoal fragments were recorded while counting the 757 terrestrial pollen.

Because relative abundance of grass pollen could be an especially important ecological indicator in mountain sagebrush-grass communities, all Fish Lake pollen counts included at least 50 grass (mean of 57, range 50 to 113). Likewise, variation in juniper and grass pollen and their small numbers in some samples called for a Diamond Pond counting plan of at least 30 grass (mean of 48, range 30 to 122) and 20 juniper pollen (mean of 42, range 18 to 92).

Percentages of terrestrial pollen are calculated for all figures, except the Fish Lake main diagram, after excluding pollen of distant conifers. Most pine pollen, with occasional grains of spruce, fir, Douglas-fir and hemlock, originates in mountains of western Oregon and northern California. Pine pollen accounts for about 14 and 23 percent of all terrestrial pollen at Diamond Pond and Fish Lake. Figure 9 shows the most important aspects of the lake core pollen analyses (for 5500 radiocarbon years) relative to the woodrat midden sequence--juniper pollen percentages, and changing relation of grass to sagebrush and charcoal to pollen.

Fish Lake

Over more than 12,000 years several subtle trends are apparent from the main Fish Lake diagram (Figure 10). Most obviously, between about 9000 and

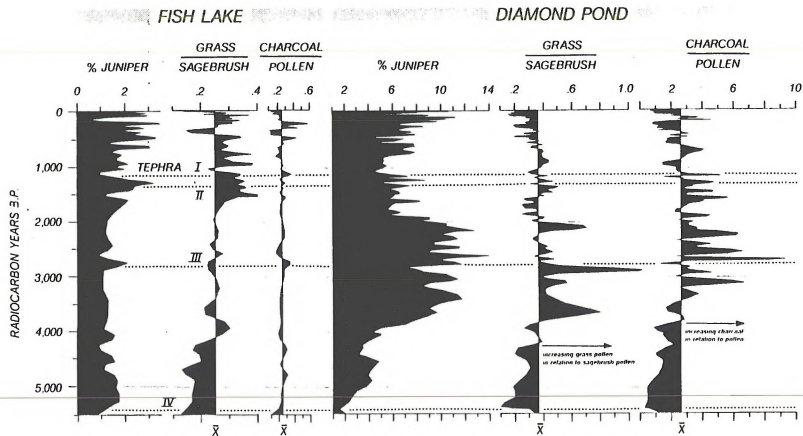


Figure 9. Three-level smoothed (normal curve smoothing function, Holloway 1985) juniper pollen percentages and ratios from Diamond Pond and Fish Lake are plotted about the mean of the average values for each 500 year interval since 5500 B.P.

FISH LAKE
STEEN'S MOUNTAIN, OREGON, 2250 Meters

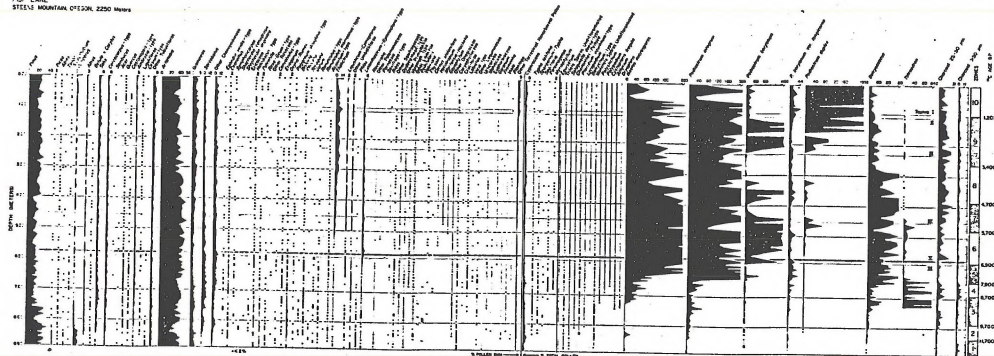


Figure 10. The main pollen diagram from Fish Lake presents analyses of samples spanning over 12,000 years—the time since ice wasted from its basin. Note that microfossil percentages are calculated differently than for the summary diagram of the last 2000 years that presents the close interval analyses (Figure 11).

FISH LAKE
(Summary Diagram to 2000 B.P.)

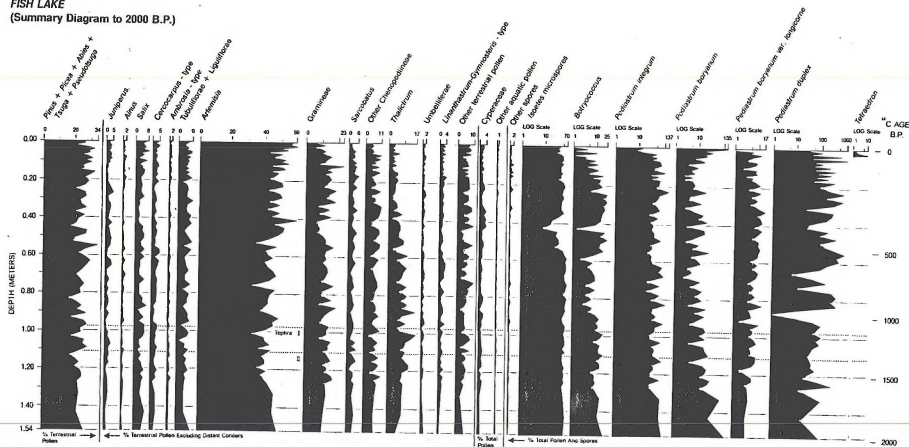


Figure 11. Summary pollen diagram of the last 2000 years for Fish Lake. In contrast to the main diagram, distant conifers are excluded from the pollen sum and algae are taken as percent of pollen and spores.

8000 B.P. quillwort (Isoetes) microspores and acid resistant algae except Pediastrum duplex (the dominant Pediastrum of the past 2000 years) increase sharply. Rising water temperatures, accompanying longer snow free summers, might account for the increasing algae with declining Potentilla and Oxyria pollen, and more abundant charcoal (Figure 10, zone 4). Overall variety of pollen and spores declines with fall of Mount Mazama (Crater Lake, Oregon) volcanic ash (Tephra VI and V) about 6800 B.P. Between 7000 and 6000 B.P. Linanthastrum-Gymnosteris, Ligusticum-Cymopterus, and most importantly Thalictrum pollen suggest developing importance of meadow margin, shady aspen grove, and high elevation talus communities that persist to the present time.

Otherwise, on first perusal the Fish Lake main and 2000-year summary pollen diagrams (Figure 11) suggest little apparent change despite close interval analyses over the past 1500 years. In one regard that impression is correct; since the glacier that occupied the basin of Fish Lake wasted more than 12,500 years ago sagebrush dominated steppe has prevailed high on Steens Mountain without the intervening forest or woodland periods seen elsewhere in the western United States (Mehring 1985, 1986). Initial (>11,000 B.P.) juniper (probably Juniperus communis) pollen abundance suggests an obviously important difference in terrestrial vegetation. Otherwise, a monotonous mix of sagebrush, distant conifers, and chenopods carried from surrounding valley floors account for most pollen deposited at Fish Lake. Yet, the relationships among two or three pollen types--as shown by their ratios or by ternary plots (Mehring 1985, figures 8, 12)--indicate short term fluctuations and long term trends revealing variations in pollen deposition.

Though not apparent from the percentage diagram, Figure 9 reveals the record of juniper pollen, grass in relation to sagebrush pollen, and variation in charcoal since 5500 B.P. The correspondence between grass (in relation to

sagebrush) and charcoal abundance over the last 2000 years is particularly striking. Today, as a result of fire suppression, the Fish Lake area on Steens Mountain is a sea of dense sagebrush (Figure 12). This fact is reflected in small charcoal/pollen and grass/sagebrush pollen ratios. Small charcoal values match the increase in sagebrush over the historic period and a similar repeated pattern is especially clear over the past 1500 years (Figure 13).



Figure 12. Fish Lake (2250 m) is surrounded by dense mountain big sagebrush and shady aspen groves (June 19, 1979).

Artificially induced low fire frequency and sagebrush abundance of today have natural analogs in recent prehistoric times. Abundant sagebrush pollen and little charcoal characterized the A. D. 1500s on Steen Mountain--just as they have in the the 1900s. This episode is preceded and followed by

FISH LAKE

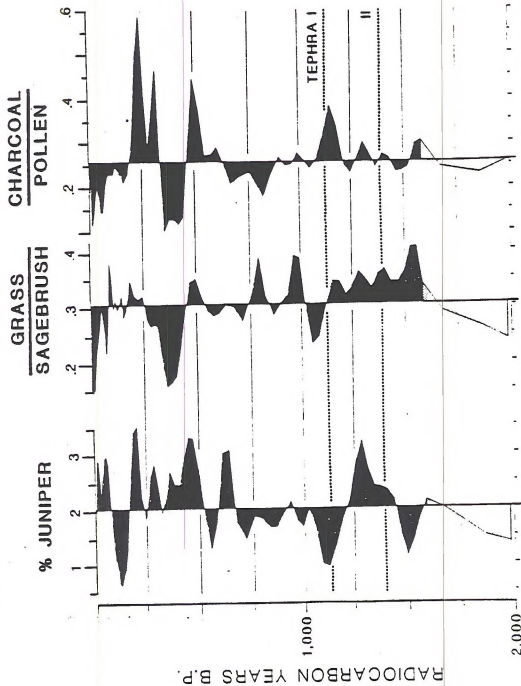


Figure 13. Smoothed juniper percent and pollen ratios plotted about the means of the means of each 500 years; closely sampled core is solid. Small juniper pollen values at Fish Lake reflect varying down slope abundance rather than established western juniper stands near the present uppermost limits of individual trees on Steeps Mountain near Fish Lake. Grass/sagebrush and charcoal/pollen ratios of this century are paralleled in the prehistoric past. Note instances where abundant sagebrush pollen (in relation to grass) coincides with small charcoal values (in relation to terrestrial pollen).

distinctively large charcoal/pollen ratios in the very late 1400s and 1600s. A similar sequence occurred about 1150 years ago (Figure 13, just above Tephra 1). With the past as guide, we can expect the importance of sagebrush to decline with a large fire and grass to prevail with continued small fires. Fire regimes resulting in this familiar pattern are not unique to the historic period of grazing and fire suppression; they have been operating in sagebrush on Steens Mountain for hundreds of years.

The additional closely spaced analyses from Fish Lake verified that juniper pollen fluctuations reflect regional downslope abundance rather than significant expanses of western juniper near the extreme upper elevational limit of individual stunted trees (Mehring and Wigand 1987, figure 3). Even the possibility of more trees on the upper woodland fringe remains limited to the last 2000 years or so, a time of maximum grass importance as measured by grass/sagebrush ratios (Figure 13). The Fish Lake pollen records suggest that--though steppe persisted through the Holocene--both terrestrial and aquatic vegetation responded to natural environmental perturbations driven by varying climate.

Diamond Pond

A summary pollen diagram for the Last 2000 years of the Diamond Pond core is presented in Figure 14; details for 2000-5000 B.P. are in Wigand (1987, figure 14). Unlike the Fish Lake diagram, the Diamond Pond diagram exhibits easily recognizable patterns of changing pollen abundance produced by local sagebrush-shadscale shrubs, grasses, juniper, and pond-fringe species (Rumex, Cyperaceae and Typha). Water depth at Diamond Pond results from regional recharge and evaporation; fossils of aquatic and pond-edge species record local water conditions. Likewise, relative abundance of Sarcobatus and other chenopod pollen reflects the importance of local shadscale species and

DIAMOND POND
(Summary Diagram to 2000 B.P.)

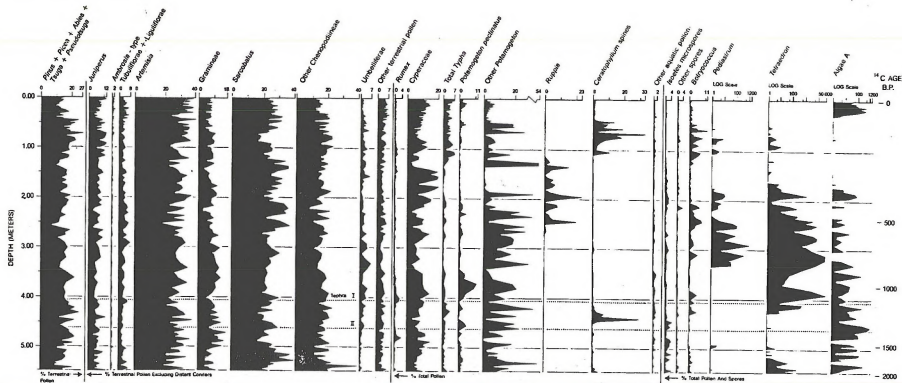


Figure 14. Summary percentage pollen diagram for 126 samples to 2000 B.P. from Diamond Pond, Oregon. Note the changing values of shrubs, pond-fringe species, aquatic plants and algae that all show variation not apparent from the woodrat middens alone. Wigand (1987) describes the 5500 B.P. Diamond Pond pollen record, with close interval sampling between 2000 and 3200 B.P., and associated macrofossils. Exclusion of pollen of distant conifers from the terrestrial pollen sum as shown here is followed in calculating percent juniper pollen in other figures. Algae A is an undetermined genus of dinoflagellate.

downwind areas of drowned or dry lake bed. Records of Ruppia, Sarcobatus, sagebrush and juniper provide especially interesting examples of past environments at Diamond Craters.

Introduction, rise and demise of ditch-grass (Ruppia maritima) and coontail (Ceratophyllum demersum), with varying values of pondweed (Potamogeton spp.), indicate changes in pond size, and water depth and quality. Ruppia thrives in brackish water and its propagules must have reached Diamond Pond thousands of times. Yet, according to fossil pollen and seeds (Wigand 1987), and excepting single samples, Ruppia was successfully established only once in over 6000 years. It persisted for nearly 400 years (A.D. 1400s to the late 1700s) then perished to be replaced by Potamogeton and Ceratophyllum (represented by seeds and by leaf spines rather than pollen). Ruppia's arrival and success coincides with large Sarcobatus pollen values and probably an episode of shallow brackish water at Diamond Pond.

The curve for Sarcobatus pollen may give the clearest clues to changing environments near Diamond Craters, particularly lake levels. Sarcobatus would have flourished with less effective moisture and shrinking lakes in the Harney Basin. Expanding lakes would first of all drown Sarcobatus habitat and that of other chenopods, among them shadscale (Atriplex confertifolia). Events of this type are important in interpreting the meaning of the Diamond Pond pollen record. Because the chenopods are prolific pollen producers; changes in their numbers will greatly influence the percentages of all other types. Therefore ratios used in describing the Fish Lake sequence are useful for Diamond Pond as well (Figures 9, 13).

Closely spaced samples of the last 2000 years clarify the continued corresponding fluctuations in percent juniper pollen and charcoal/pollen ratios. They also show that grass/sagebrush ratios do not follow the earlier

(3800-2000 B.P.) pattern. Marked increase in sagebrush pollen (in relation to grass) at Diamond Pond after 2000 B.P. contrasts with increasing grass pollen (in relation to sagebrush) at Fish Lake. At both sites, pollen records of the last 2000 years are quite distinctive as compared with the preceding 2000 years. Though different, and separated by 1000 m in elevation, they follow the same chronological trends; this suggests responses to regional climatic differences (Figure 9).

If like Janus we could face the past and see the future, trends like these would become important in understanding long term directions of the differences we see. Such a view illuminates the events of a hundred years with the lights of a thousand and more. In western North America sagebrush's historic dominance sometimes has been attributed to too much grazing and too little fire--events unique to the last 100 years or so. Yet, the record of sagebrush pollen from southeastern Oregon dictates otherwise. Though cows and fire suppression may well have favored sagebrush, at Fish Lake its historic success has parallels in the recent prehistoric past (Figure 13).

Diamond Pond's sagebrush/chenopod pollen ratios suggests the possibility of 5000 years of increasing sagebrush in valleys and on the lower slopes surrounding Steens Mountain (Figure 15). Shorter term variations represent climate induced oscillations in area of shadscale and expanding or contracting lakes (Figure 16). Atop Steens Mountain near the upper limit of sagebrush at Wildhorse Lake, pollen has blown from valleys below to give a regional synthesis of sagebrush importance and its occasional local occurrence; here the regional trend of increasing sagebrush in relation to chenopod pollen extends to 8000 B.P. (Figure 17).

After sagebrush, juniper is among the most maligned of grass replacing native genera to be called "invader." Neither flame, chain, bulldozer, saw,

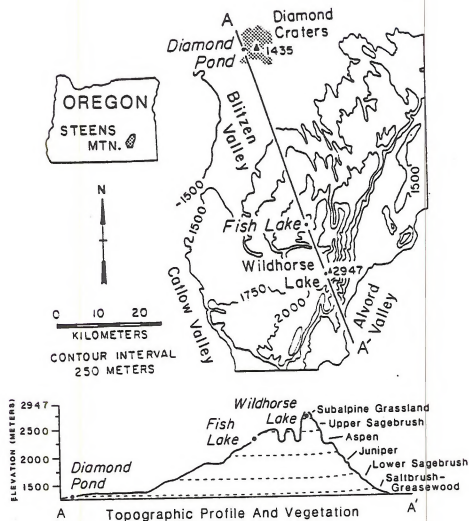


Figure 15. Generalized distribution of major vegetation units and topographic profile from Alvord Valley to Diamond Craters.

poison, committees nor conferences have halted its historic advances. Like sagebrush, modern expanses of juniper have parallels in the late Holocene. Juniper pollen from Diamond Pond is an interesting indicator of vegetation change on the slopes of Diamond Craters because macrofossils from woodrat middens confirm juniper's varying importance near its present lower elevational limits.

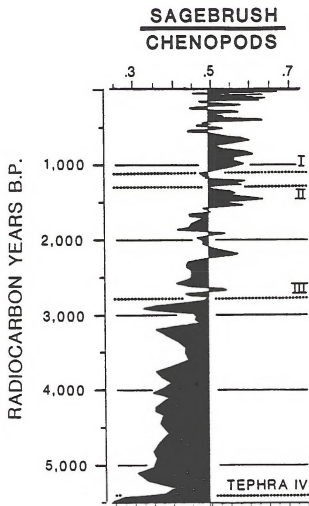


Figure 16. This sagebrush/chenopod pollen ratio from Diamond Pond follows the long-term trend of increasing sagebrush pollen production in the present lower sagebrush zone (in relation primarily to *Sarcobatus* and *Atriplex*) that is indicated by the same ratio at Wildhorse Lake (Figure 17).

JUNIPER FROM WOODRAT MIDDENS AND LAKE CORES

Juniper pollen from a closely sampled core and radiocarbon dated juniper macrofossils from nearby woodrat middens give a notion of western juniper's history and the relative significance of its recent success--despite chaining, bulldozing, cutting, poisoning and burning. Detailed pollen analyses was necessary to evaluate apparent correspondence between the radiocarbon ages of juniper dominated middens and distinct episodes of abundant charcoal and

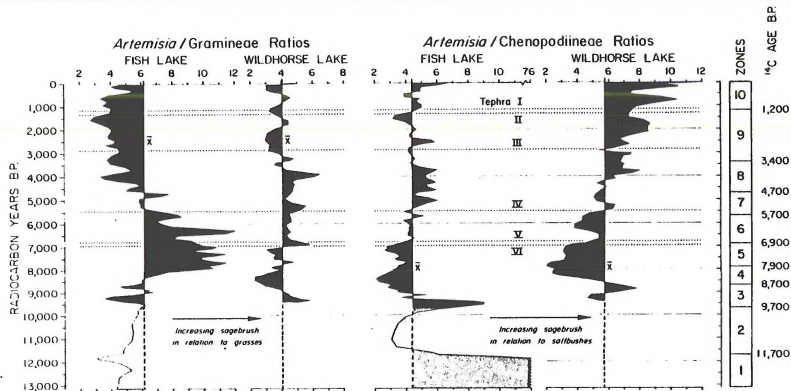


Figure 17. Three-level smoothed pollen ratios plotted about the means of the last 9700 and 9300 radiocarbon years (does not include new close interval analyses). Where percent pollen shows few apparent differences, ratios may be more informative. For example, increasing sagebrush in relation to grass at Fish Lake (2250 m) most probably signals less effective moisture. The same variation at Wildhorse Lake (315 m-higher), at the current upper elevational limit of sagebrush, suggests upward advance of sagebrush owing to warmer conditions with fewer snow patches lasting into summer.

Relationship of sagebrush to *Sarcobatus*, *Atriplex* and other chenopods probably reflects local relative abundance of sagebrush at Fish Lake as compared to wind-born sagebrush and chenopods from lower elevations. At Wildhorse Lake atop Steens Mountain local pollen production is small and the ratio synthesizes regional abundances blown from surrounding desert valleys and also the occasional local importance of sagebrush. The relative long-term increase in sagebrush pollen over chenopod pollen since 8000 B.P. is also seen at Diamond Pond.

juniper pollen (Figures 7, 9; Mehringer and Wigand 1987, figure 4). Also, using the pollen and seeds of aquatic plants from Diamond Pond cores, Wigand (1987, figure 24) recognized these same general periods as times of relatively deeper water. The apparent clustering of radiocarbon ages of middens became as intriguing as their macrofossils and pollen.

Though different from present in their abundant juniper, Diamond Craters' middens from rimrock and lava tubes lacked some events apparent in the fossil sequence from Diamond Pond's mud. Nonetheless, ages of middens corresponded closely to other events marked by juniper pollen and indicators of deeper water. Because these apparent agreements came from two independently dated series (juniper or woodrat fecal pellets, and lake sediments) their comparison required that we consider:

1. potential for contamination in different environments,
2. short-term perturbations in ^{14}C production,
3. and progressive disparity between radiocarbon and sidereal calendar years resulting in a 1000-year discrepancy from 2000 to 7000 years ago (Stuiver et al. 1986).

We evaluated potential for contamination with selection and pretreatment of samples before they were dated. The latter two considerations led us to convert radiocarbon ages to calendar years (Robinson 1986) in presenting the woodrat midden-Diamond Pond core comparisons (Figure 18).

Because of natural variations in atmospheric ^{14}C , a single radiocarbon age may have more than one calendar date and the standard deviation may be considerably larger than indicated by counting statistics alone. It was conceivable that the pattern of dates of juniper dominated woodrat middens (Figure 7) was, in part, an artifact of differences in rates of radiocarbon production. The Diamond Pond core samples, on the other hand, are in

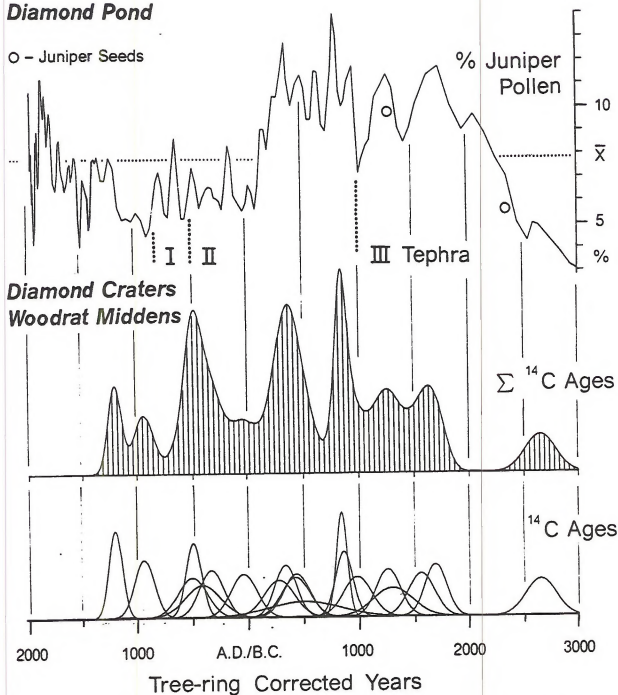
Diamond Pond

Figure 18. Smoothed Diamond Pond juniper pollen percentages (Figure 9) and tree ring corrected woodrat midden dates plotted with two standard deviations (Table 2).

stratigraphic order. Changing patterns of juniper values are in proper sequence regardless of how accurately they are dated. Also, in this case, close interval analyses showed the juniper pollen peaks to gradually rise and fall over several samples representing a decade, a century, or longer.

To confirm that clusters or single radiocarbon dates from woodrat middens matched periods of larger juniper pollen values, both data sets were calibrated to calendar years. Of special interest was the apparent double peak of midden dates around 2360 and 2700 B.P. that corresponded to distinctive events in tree ring correction curves of radiocarbon ages (Pearson 1986; Robinson 1986). By comparing Figures 7 and 18 it is clear that tree ring corrections do not alter the pattern of dates, but further distinguish the peaks (tree ring corrected to about 440 and 870 B.C.) that match the independently dated largest juniper pollen percentages. Thus, distribution of woodrat midden dates is not merely an artifact of perturbations in atmospheric ^{14}C .

TREE RINGS, POLLEN AND CHARCOAL

Having established the chronological correspondence between individual juniper-containing middens and the continuous record of juniper pollen from Diamond Pond, it is appropriate to ask what the juniper pollen percentages represent (e.g., numbers of trees, stages of woodland development, pollen production, responses to fire or drought). Figures 19 and 20 illustrate the distribution of samples analyzed over 12 and 2.5 meters of the Diamond Pond core. All samples are 1 cm-tall; however, deposition rates varied. A sample at 7.4 m (4000 years ago) represents about 10.4 years, at 2.0 m (400 years ago) about 2.6 years, and at 0.30 m (40 years ago) about 1.4 years. Greater variation among adjacent samples would be expected as years per sample

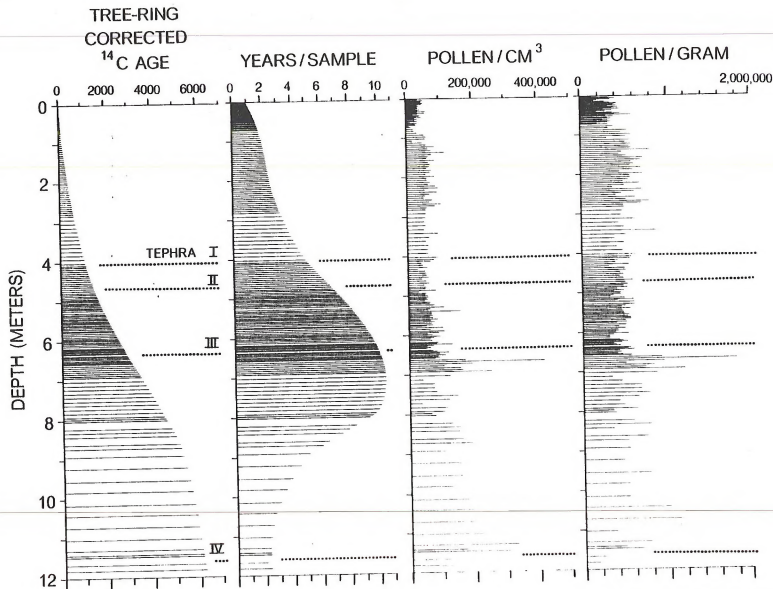


Figure 19. Distribution of 195 pollen samples spanning the past 6300 tree ring corrected radiocarbon years B.P. (about 4300 B.C.) from 12 meters of Diamond Pond Core. All samples are 1-cm tall, but because deposition rates vary individual samples may contain from one to 11 years. Though some mixing in the bottom sediments no doubt tends to smooth variation in pollen deposited annually, it does not explain similarity in pollen influx over the last 3000 years (6.2 m) despite changing deposition rates. In short, pollen accumulation rates from Diamond Pond are suspect; they are used here only for the last 500 years in Figure 15.

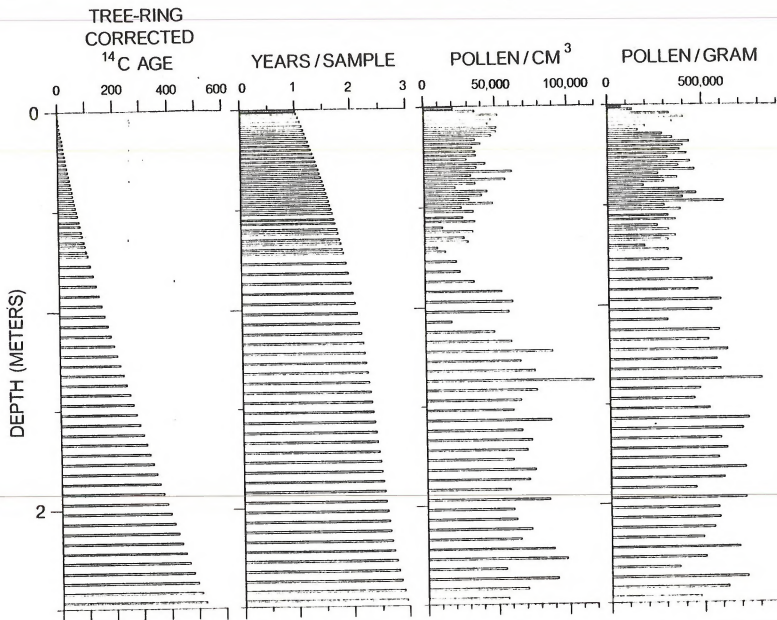


Figure 20. Distribution of 67 pollen samples spanning the last 500 tree ring corrected radiocarbon years. Each sample is 1-cm tall and contains, on the average, one to three years.

decreased; the factor(s) being measured would also change. Thus, the apparent response of juniper as discerned from its fossil pollen is partly a matter of scale.

A series of pollen analyses of samples averaging 10 years duration might record a wave of juniper expansion or decline. Another averaging a year or two could reveal shorter events along the wave's crest such as differences in vigor of pollen producing trees, or the immediate effects of fire or disease. Agreement between broad swells in the pollen and macrofossil records clearly represents the former (Figure 11). The latter is apparent, though not fully understood, in the details revealed by comparisons of tree rings with juniper pollen and charcoal (Figure 21).

Though potentially giving the best estimates of juniper pollen abundance, pollen accumulation rates are suspect at Diamond Pond. Because the small basin has steep slopes and sediments have varied (Wigand 1987) pollen and charcoal accumulation rates were influenced by intensity of storms and vegetation cover's ability to impede slope wash. Changing water depth, surface area, aquatic vegetation, and the filtering fringe of bulrushes and cat-tails have all influenced depositional environments. Recirculation in dry desert dust might also operate to increase annual influx of pollen during droughts.

Pollen percentages are influenced by constraints that may act in concord with environmental factors to emphasize small juniper pollen values. In droughty periods such as the 1930s, juniper pollen production could have faltered with vigor of the trees. Also, Harney and Malheur lakes were small or completely dry (Piper et al. 1939); prolific pollen producers, such as Atriplex and Sarcobatus, invaded their empty beds. Thus, percent juniper pollen might have declined even more as Malheur Lake shrank. Perhaps it is

this combination of factors that affords such good agreement to the juniper pollen-woodrat midden chronology-water depth indicators. I explore this possibility by reference to details of the past 500 years and by comparing pollen and charcoal values with a tree ring series from western juniper (Holmes et al. 1986).

Over 50 years ago Jessup (1934) recognized a relationship between wide annual rings in eastern Oregon's western junipers and plentiful precipitation. According to recent studies of climate response functions from tree rings and monthly weather records, mild winters with ample precipitation and cool springs favor wide annual rings in western juniper (Earle and Fritts 1986:90; Fritts and Xiangding 1986:38). The same factors would lead to larger lakes with loss of lake bed and playa-edge pollen producers and relatively more juniper in the regional pollen rain--even if juniper pollen production were unaffected. The smallest juniper values (juniper $\text{cm}^{-2}\text{yr}^{-1}$ and percent) in the last 500 years coincide with a distinct tree ring recorded drought of the early 1500s and with abundant charcoal (Figure 21). For the next 200 years juniper values build gradually while charcoal values decline. Together with the charcoal, this sequence suggests that junipers were relatively abundant by the late 1700s, but waned with multiple burns through the 1860s. Further decline in the 1890s may reflect drought and cutting by early settlers.

Juniper expansion of the last 100 years is historically documented; yet, Figure 21 shows a complicated sequence. Juniper pollen production must have varied with vigor wrought by vagaries of short sharp events in annual distribution of precipitation and temperature, and by barely perceptible maturation of pollen producing trees. As a matter of constraint alone, percent juniper pollen also rose and fell with expanding and shrinking lakes in the Harney Basin. These effects are seen especially in the increases in

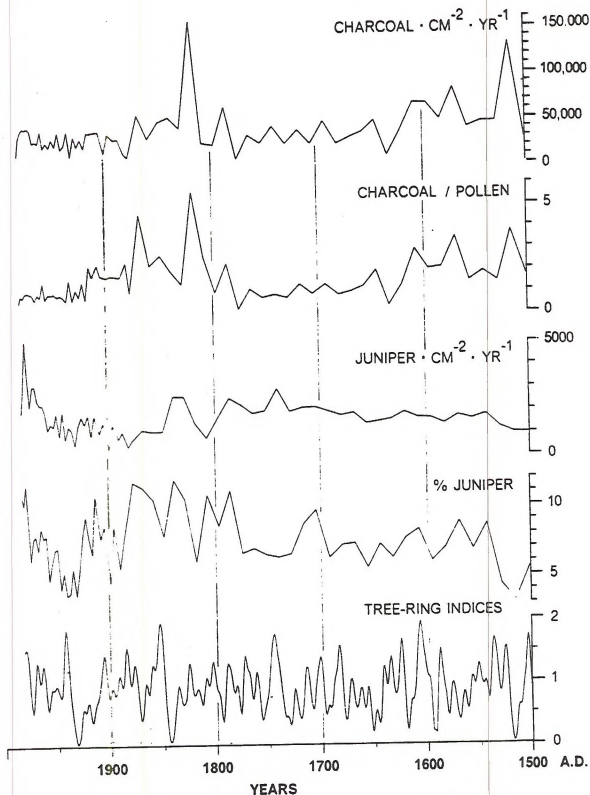


Figure 21. A comparison of 13-level smoothed tree ring indices (low-pass filter, Fritts 1976:270) of western juniper (*Juniperus occidentalis*) from Little Juniper Mountain, Oregon (Holmes *et al.*, 1986:90), with percent juniper pollen (Figure 9), the charcoal/pollen ratio, and accumulation rates of juniper pollen and charcoal for 67 Diamond Pond samples dating from A.D. 500.

the early 1900s, the precipitous fall through the drought of the 1930s, and the sharp rise thereafter. Accumulation rates show relatively small numbers of juniper pollen from about 1850 to 1940--with distinct fluctuations matching declines in percent juniper during the 1890s and 1930s--then a five-fold increase to the 1980s.

Relatively little charcoal and rising juniper values chronicle fire suppression (Steele et al. 1986) and expanding woodlands over the last 50 years. Perhaps trees from the first waves of historic expansion are now reaching their potential for pollen production, while the post 1930s trees are beginning to contribute as well. The lag between juniper stand establishment and significant contributions to the regional pollen rain is not obvious over centuries or millennia because samples containing more years smooth events that even then are considerably shorter than the uncertainties in radiocarbon dates. Thus, chronological agreement between juniper pollen values from cores, and macrofossils and pollen from woodrat middens is all the more remarkable.

Despite limitations, relationships between tree ring widths, and pollen and charcoal values since A.D. 1500 demonstrate the applicability of fossil records in explaining natural variation in eastern Oregon's steppe and woodland. Further understanding will require a more precise chronology of the last 200 years through detailed Cesium-137 and Lead-210 dating of the Diamond Pond and Fish Lake cores. Comparisons with western juniper fire-scar chronologies and stand characteristics (Eddleman 1987; Young and Evans 1981) at Diamond Craters and on Steens Mountain could help to evaluate these findings of the last few hundred years and to calibrate them for interpreting longer records. For example, would fire scar studies indicate that charcoal differences (e.g., between A.D. 1650-1750 and A.D. 1760-1860) resulted from changes in regional fire frequency or intensity, or both?

For whatever reasons, charcoal and juniper pollen values seem related on a scale of decades (Figure 21) or centuries (Figure 9). Over the last 500 years juniper values generally fell with fire and rose with declining charcoal. The period of corresponding greatest juniper pollen and chronological clusters of juniper-containing woodrat middens (2200-3600 B.P.) also shows the largest charcoal/pollen and grass/sagebrush ratios. On a scale of centuries it was a time when abundant juniper fueled the fires that favored grass and discouraged sagebrush (Figure 9). Charcoal from the midden pollen samples confirms its general abundance during this period of juniper pollen importance at Diamond Pond (Table 3).

DISCUSSION

I have described the relationships of three kinds of information bearing on the vegetation history of southeastern Oregon--macrofossils from woodrat middens, pollen from woodrat middens and pollen from cores. Macrofossils from Diamond Pond cores are described by Wigand (1987). In addition I have attempted to decipher the message left by charcoal fragments in the pollen samples. The most detailed information for a single time at a single locality comes from the woodrat midden macrofossils. This series contains 54 identified taxa with as many as 34 in a single midden. Taken individually or as a group, they indicate a landscape with juniper more widespread, but otherwise little different than now. Though apparent clusters of dates might be intriguing, the Diamond Craters' midden macrofossils, taken by themselves, suggest neither varying environments nor the potential significance to the pattern in their ages.

Pollen analyses of Graben Dome and Nolf Crater middens confirmed preeminence of juniper and sagebrush, and may indicate their regional

importance as well. However, uncertainty of their near or distant origin, and the collecting proclivities of woodrats limit utility of these data that give few additional clues to the nature or richness of the local flora. Charcoal fragments in the pollen samples suggest close by and distant fires. Pollen also revealed local absence and apparent regional unimportance of western juniper while a midden from the Catlow Rim, at Three Mile Creek, accumulated about 6100 B.P.

Because macrofossils in the middens must have come from within the 50 m or so that woodrats are known to forage, these midden records indicate actual movement of juniper populations rather than simply increased density. I anticipated this, but could not have proven it with the pollen data alone. The woodrat midden macrofossils gave local vegetational detail and woodrat midden pollen spectra reinforce a similar interpretation of juniper and sagebrush dominance. But, only pollen, seeds and algae from the lake cores suggested the pace and regional importance of environmental change. Woodrat midden fossils offered no indications of trends such as increasing sagebrush at lower elevations since 8000 B.P. and relative abundance of grass in relation to sagebrush high on Steens Mountain over the past 2000 years.

Together, pollen of aquatic and terrestrial species from Diamond Pond afford a measure and a sequence of past climatic fluctuations lacking from the midden records. Without the midden fossils, however, one could only surmise that Oryzopsis, Sitanion and Stipa were important grasses or that genera producing little or indistinct pollen but sharing importance with western juniper in middens elsewhere, such as Purshia and Cercocarpus (Mehringer and Wigand 1987, table 2), were absent from the flora of Diamond Craters during the last 5000 years.

Though different from present in their abundant juniper, Diamond Craters' middens come short of recording events along the hard rimrock that left clear tracks in the mud of Diamond Pond. Nonetheless, ages of middens corresponded closely to some of these events. Complacency of the woodrat midden assemblages is not well explained by unchanging Holocene vegetation on basalt flows and rimrock, nor by midden records that send only a very local and different signal than pollen from cores. In fact, the midden macrofossils and Diamond Pond microfossils come together comfortably in a scenario of waves of juniper crossing a sagebrush sea in times of high water. It seems that Diamond Craters middens date to periods that favored western juniper in the present lower sagebrush zone and thereby, perhaps, woodrats as well.

Without Diamond Pond's continuous sequence the regional supremacy of sagebrush, punctuated by episodes of juniper, grass, shadscale and the charcoal that chronicles fire, would remain unknown. Without woodrat middens the details of the paleoflora and vegetation history would remain unclear. Together the two lend greater resolution than either alone. Secrets of past vegetation at Diamond Craters await recovery, dating and study of additional woodrat middens; their ages alone would compliment these investigations.

CONCLUSIONS

Pollen analysis of cores from Fish Lake and Diamond Pond, combined with macrofossil studies of ancient woodrat middens, provide historical perspectives on steppe and woodland in eastern Oregon. Through the fossil records I investigated vegetation change and accessed the relative role of fire as revealed by the varying abundance of microscopic charcoal. I also matched the fossil pollen and charcoal sequences to tree ring indices of western juniper to evaluate association of climate change and fire with

spread, maintenance, and decline of woodland and steppe. These studies suggest most clearly that, for the Steens Mountain region, fire regimes and the magnitudes of responses of juniper and sagebrush over the last century are not unique to the historic period, and that:

1. At Diamond Craters woodrat middens from 100 m to 1 km from the nearest living junipers--for the most part evidencing historic expansion--were dominated by western juniper remains. Radiocarbon dates of these middens ranged from 4075 to 835 B.P.
2. Juniper pollen from a closely sampled core and the radiocarbon dated juniper macrofossils from nearby woodrat middens give a notion of western juniper's history and the relative significance of its recent success. Western juniper is riding the tides of changing climate. Though Holocene juniper abundance has changed considerably near its lower elevational limits, there has been no such corresponding spread near its present upper limits.
3. The great juniper expanses of about 3600-2200 B.P. are characterized by abundant grass and a fire regime promoting abundant charcoal. This period and others of juniper importance coincide with deep water phases in Diamond Pond and probably with higher regional water tables.
4. Tree ring widths, and juniper pollen and charcoal values since A.D. 1500 at Diamond Pond show relationships between drought, fuel and fire. Most importantly they place early descriptions and early photographs from the 1800s in a period of declining juniper pollen and unusual charcoal abundance. Slightly earlier, in the late A.D. 1600s and early 1700s, conditions that brought increasing juniper pollen and charcoal values comparable to those of the last 50 years no doubt would have left different perceptions of the pristine state in steppe primeval.

5. Artificially induced low fire frequency and sagebrush abundance of today have analogs in recent prehistoric times. They may have gone unrecognized because we lack the evidence and because travelers' tales from the times of Lewis and Clark, Ogden, and others, are often thought to reveal "the natural" (i.e., correct) conditions. But, these tales come from impressions of glimpses of ever changing landscapes; they are not evidence for a stable "natural" state that we should necessarily attempt to replicate.

Abundant sagebrush pollen and little charcoal characterized the A.D. 1500s on Steens Mountain--just as they have in the the 1900s under the influence of grazing and fire suppression. This episode is preceded and followed by distinctively large charcoal values in the very late 1400s and the 1600s. A similar sequence occurred about 1150 years ago. The pattern of sagebrush-eradicating fires, subsequent success of grass, and eventual return of sagebrush has been operating on Steens Mountain for hundreds of years. In short, sheep, cows and fire suppression may well have favored sagebrush near Fish Lake; still, like juniper, modern expanses of sagebrush have parallels in the late Holocene.

6. The Diamond Pond and Wildhorse Lake pollen records indicate that present sagebrush abundance--at least in the lower sagebrush zone--may be the culmination of a regional trend toward increasing sagebrush that began 8000 to 5000 B.P.
7. The past offers a positive perspective on the future.

LATE HOLOCENE ENVIRONMENTS ON THE
NORTHERN PERIPHERY OF THE GREAT BASIN

APPENDIX A
INVESTIGATIONS AT BLUE LAKE, NEVADA
AND
JORDAN CRATERS, OREGON

Final Report to
Bureau of Land Management
Oregon State Office, Portland
for Contract YA551-CT5-340075
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Blue Lake, Pine Forest Range, Nevada

Introduction

Testing of Blue Lake was considered in this study because reconnaissance of the Pine Forest Range indicated potential for relating fire-scar studies of the isolated white pines to charcoal accumulation estimates from lake cores. Also, fossils from the sediments of Blue Lake might prove important in tracing the history of isolated conifers in the northern Great Basin and provide a comparison with the paleoenvironmental records from the higher and larger Steens Mountain that supports steppe, yet lacks native pines.

In the technical proposal I indicated reservations about including studies of Blue Lake. These were born out by the inability of BLM to provide the fire scar studies required by the proposal and by last minute complications arising from perceptions of conducting such studies in a BLM Wilderness Area. Despite these problems--with assistance of BLM personnel, Oregon volunteers, Boy Scouts from Winnemucca, Nevada, and colleagues from Washington State University--we arrived at Blue Lake on July 15 and continued our investigations on schedule through July 22, 1986 (Figures 1, 2).

The Washington State University team included Joy and Ronald Mastrogioseppe of the Marion Ownbey Herbarium (WSU) and the National Park Service (Redwoods). Ron's experience as a forest and fire ecologist led to evaluation of the potential for fire-scar studies. Joy's plant collections (Table 1) are in the Marion Ownbey Herbarium or in the seed and pollen reference herbarium, Department of Anthropology, Washington State University.

Table 1. Plants collected in the vicinity of Blue Lake (2432 meters), Pine Forest Range, Nevada.

Family	Genera and Species
CAPRIFOLIACEAE	<u>Symphoricarpus oreophilus</u>
CARYOPHYLLACEAE	<u>Arenaria aculeata</u>
COMPOSITAE	<u>Antennaria microphylla</u> , <u>Arnica mollis</u> , <u>Arnica chamissonis</u> ssp. <u>foliosa</u> var. <u>incana</u> , <u>Achellia millifolium</u> , <u>Artemisia arbuscula</u> , <u>A. tridentata</u> , <u>A. ludoviciana</u> var. <u>latiloba</u> , <u>Aster chilensis</u> var. <u>adscendeus</u> , <u>A. occidentalis</u> var. <u>occidentalis</u> , <u>Chrysothamnus nauseosus</u> var. <u>albicaulis</u> , <u>Erigeron compositus</u> var. <u>glabratus</u> , <u>Erigeron lanatum</u> var. <u>lanatum</u> , <u>Haplopappus hirtus</u> var. <u>lanulosus</u> ,
CRUCIFERAE	<u>Arabis holboellii</u> var. <u>pendulocarpa</u> , <u>Barbarea orthoceras</u>
CYPERACEAE	<u>Carex aquatilis</u> var. <u>aquatilis</u> , <u>C. athrostachya</u> , <u>C. atrata</u> , <u>C. aurea</u> , <u>C. douglasii</u> , <u>C. exserta</u> , <u>C. hoodii</u> , <u>C. lanuginosa</u> , <u>C. microptera</u> , <u>C. multicostata</u> , <u>C. nebraskensis</u> , <u>C. rostrata</u> , <u>C. subfusca</u> , <u>C. vallicola</u> , <u>Eleocharis acicularis</u> , <u>E. palustris</u>
GENTIANACEAE	<u>Gentiana affinis</u>
GRAMINAE	<u>Agrostis idahoensis</u> , <u>Festuca ovina</u> , <u>Phleum alpinum</u> , <u>Stipa pinetorum</u>
GROSSULARIACEAE	<u>Ribes velutinum</u> var. <u>velutinum</u>
HALORAGACEAE	<u>Myriophyllum exalbescens</u>
HYDROCHARITACEAE	<u>Elodea nuttallii</u>
IRIDACEAE	<u>Iris missouriensis</u>
ISOETACEAE	<u>Isoetes bolanderi</u>
JUNCACEAE	<u>Juncus balticus</u> var. <u>montanus</u> , <u>J. ensifolius</u> var. <u>ensifolius</u>
LABIATAE	<u>Agastache urticifolia</u> .

Table 1. Continued

LEGUMINOSAE	<u>Lupinus caespitosus</u> , <u>L. caudatus</u>
OROBANCHACEAE	<u>Orobanche californica</u> var. <u>corymbosa</u>
PAEONIACEAE	<u>Paeonia brownii</u>
PINACEAE	<u>Pinus albicaulis</u> , <u>P. flexilis</u>
POLEMONIACEAE	<u>Phlox diffusa</u> var. <u>diffusa</u>
POLYGONACEAE	<u>Eriogonum strictum</u> var. <u>flavissimum</u> , <u>Polygonum amphibium</u> , <u>P. coccinium</u> , <u>Montia chamissoi</u>
POTAMOGETONACEAE	<u>Potamogeton richardsonii</u>
RANUNCULACEAE	<u>Ranunculus aquatilis</u> var. <u>capillaceus</u>
RHAMNACEAE	<u>Ceanothus velutinus</u>
ROSACEAE	<u>Cercocarpus ledifolius</u> var. <u>ledifolius</u> , <u>Amelanchier alnifolia</u> , <u>Holodiscus dumosus</u> , <u>Potentilla concinna</u> (?), <u>P. glandulosa</u> var. <u>nevadensis</u>
SALICACEAE	<u>Populus tremuloides</u> , <u>Salix lemmonii</u>
SCROPHULARIACEAE	<u>Castilleja viscidula</u> , <u>C. applegatei</u> <u>Mimulus primuloides</u> , <u>Penstemon fruticosus</u> , <u>P. procerus</u> var. <u>formosus</u>
UMBELLIFERAE	<u>Osmorhiza occidentalis</u> , <u>Sphenosciadium capitellatum</u> ,

The whitebark pine (Pinus albicaulis) woodland surrounding Blue Lake also contains a few limber pines (Pinus flexilis). It is typical of subalpine forest in having only local accumulations of dead and downed wood on steep slopes. Nonetheless, there are small areas (<5 acres) of dense trees that could support a crown fire under conditions of low humidity, low fuel moisture and high winds. Such a crown fire would most likely spread upslope from the shrub grass vegetation below. Though charcoal lenses and charred plant macrofossils from sediments of Blue Lake revealed severe fires in the past, the search for fire scars on living trees was less successful.

The Mastrogiuseppe's found many whitebark pines on the lower slopes with apparent porcupine damage; a few exhibited the classical A-shaped scar on their upslope sides characteristic of fire damage. Growth healing these apparent fire-scars contained 60 to 70 annual rings. The tree-ring cores, however, did not reveal distinct charcoal layers and further testing is unlikely to prove productive under the restrictions imposed on such activities in this wilderness area.

Cores and Sediments

Cores were raised from within a 10-meter radius, beneath about 14.5 meters of water, near the center and deepest part of Blue Lake's eastern arm. The coring raft, attached to shore by lines from its four corners, supported a working platform and drive tower from which 3-meter long, 10-centimeter diameter plastic core barrels could be driven and retrieved with hoists (Figures 1, 2); 15-centimeter diameter plastic pipe served as temporary casing. Core barrels were sawed to the length of sediment recovery, capped and sealed. They were placed in refrigerated storage upon return to Washington State University; they should remain well preserved and available for study for at least another year.

Sediments were exposed for description by making two shallow cuts the length of the core and removing half of the plastic barrel. In this manner the deposits were protected during transport and not distorted by extrusion.

While describing the sediments we examined the cores for charcoal and plant macrofossils. The 4.50 meters of Blue Lake sediments begin with redeposited volcanic ash from Mount Mazama (Crater Lake, Oregon). They represent laminated sand to clay deposits with distinct layers of primary air fall or redeposited volcanic ash, sponge spicules, Cladocera exoskeletons, and charred plant debris (Figure 3).

The composite core log (Table 2) is obtained from the most complete and undisturbed sections of the four nearby coring localities. The cores were correlated by distinctive stratigraphic markers and depth. In describing the sediments, color (moist and dry) was determined with the Munsel Color Chart. Bands differ primarily in color whereas laminae differ in texture; their description follows Soil Survey Manual (Soil Survey Staff 1951) terminology for platy structure. Distinctness and topography of the lower boundary of each unit are indicated by Soil Survey Manual (Soil Survey Staff 1951: 139) abbreviations. However, following Mehringer and Sheppard (1978), the measurements for boundary distinctness differ as follows: very abrupt (<1 mm), abrupt (1-2 mm), clear (2-4 mm), gradual (4-8 mm), diffuse (8-16 mm).

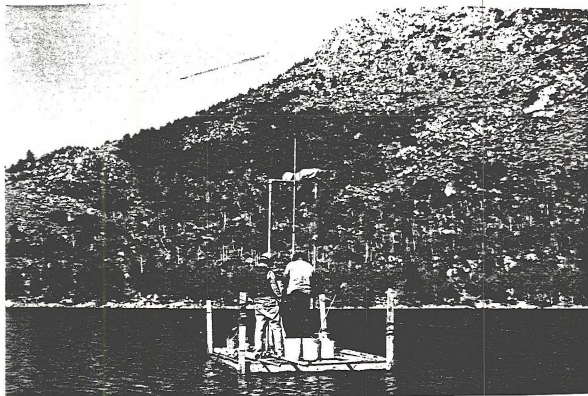


Figure 1. Coring Blue Lake, Pine Forest Range, Nevada (July 1986).

Table 2. Core description, Blue Lake, Pine Forest Range, Nevada.

DEPTH (meters)	DESCRIPTION
0.000-0.265	Silty gyttja with many very fine to fine bands (0.5 to 4.0 mm thick) from 2.5Y 4/2 dark grayish brown (moist), 2.5Y 7/2 light gray (dry), to 2.5Y 3/2 very dark grayish brown (moist), 5Y 4/3 olive (dry); sponge spicules at 0.022 to 0.020 m. Non sticky, non plastic; abrupt, smooth.
0.265-1.295	Silty clay gyttja with many very fine to medium bands (0.5 to 18.0 mm thick) from 2.5Y 4/2 dark grayish brown (moist), 2.5Y 7/2 light gray (dry), to 2.5Y 3/2 very dark grayish brown (moist), 5Y 4/3 olive (dry); volcanic ash at 0.876 to 0.874 m, 2.5Y 5/2 grayish brown (moist), 5Y 8/1 white (dry); charcoal-rich laminae at 0.405 to 0.395 m and 0.9855 to 0.9845 m 5Y 2.5/2 black (moist), 2.5Y 4/2 dark grayish brown (dry); sponge spicules at 0.943-0.945 m, 5Y 4/3 olive (moist), 5Y 8/1 white (dry). Very slightly sticky, very slightly plastic; abrupt, smooth.
1.295-1.683	Silty clay gyttja with many very fine to medium bands (0.5 to 18.0 mm thick) from 2.5Y 4/2 dark grayish brown (moist), 2.5Y 7/2 light gray (dry), to 2.5Y 3/2 very dark grayish brown (moist), 5Y 4/3 olive (dry); laminae with sponge spicules at 1.341 to 1.338, 1.376 to 1.373 (double band; faulted?), 1.490 to 1.489, 1.551 to 1.549, 1.5640 to 1.56395, 1.578 to 1.570, 1.5840 to 1.5835, 1.625 to 1.623, and 1.640 to 1.637 m, six 0.5 mm-thick laminae of sponge spicules centered at 1.668, 1.662, 1.659, 1.657, 1.653 and 1.7162 m, and three 1 mm-thick laminae of sponge spicules at 1.682, 1.678 and 1.673 m, 5Y 4/3 olive (moist), 5Y 8/1 white (dry). Very slightly sticky, very slightly plastic; abrupt, smooth.
1.683-2.922	Silty clay gyttja with many very fine to medium bands (0.5 to 12.0 mm thick) from 2.5Y 4/2 dark grayish brown (moist), 2.5Y 7/2 light gray (dry), to 2.5Y 3/2 very dark grayish brown (moist), 5Y 4/3 olive (dry); volcanic ash at 1.993 to 1.991 m 2.5Y 5/2 grayish brown (moist), 5Y 7/1 light gray (dry); sponge spicules at 1.956 to 1.954, 1.9520 to 1.9515 and 2.1050 to 2.1045 m, five washed-in or drift layers from 2.243 to 2.151 m and 2.287 to 2.243 m; upper unit grades from clean fine sand (2.243 to 2.237 m) through charcoal-rich fine sand and silt (2.237 to 2.183 m), to clay (2.183 to 2.151 m); lower unit consists of clean fine sand (2.287 to 2.281 m) overlain by silt with discontinuous laminae of fine sand and charcoal (2.281 to 2.243 m) terminated by clean sand. Charcoal-rich laminae from 2.355 to 2.352, 2.3705 to 2.3700 and 2.3780 to 2.3775 m. Slightly sticky, slightly plastic; abrupt, smooth.

Table 2. Continued.

2.922-3.859	Slightly sandy, silty clay gyttja with many very fine to medium bands (0.5 to 18.0 mm thick) from 5Y 4/2 olive gray (moist), 5Y 5.5/2 olive (dry) to 5Y 3/2 dark olive gray (moist), and 5Y 5.5/3 olive (dry); sponge spicules at 3.1370 to 3.1365, 3.132 to 3.1315 and 3.2420 to 3.2415 m. Tephra layer (2 mm thick) at 3.606 m. Laminae (1 to 2 mm thick) of fine to coarse sand at 3.116, 3.204, 3.420, 3.587, 3.641 and 3.688 m. Thick unit of organic detritus from 3.079 to 3.000 m, 5Y 2.5/1 black (moist), 2.5Y 3/2 very dark grayish brown (dry), consisting of three subunits: a) charcoal-rich silt (3.079 to 3.052 m), b) charred organic detritus of leaves, twigs, seeds and pine needles (3.052 to 3.024 m), and c) charcoal-rich silt (3.014 to 3.000); additional charcoal-rich unit from 3.256 to 3.244 m. Distinctive laminae (<0.5 mm thick) with abundant Cladocera remains at 3.172, 3.204, 3.238, 3.302, 3.309, 3.321, 3.328, 3.347, 3.350, 3.541, 3.560, 3.593, 3.640, 3.702, 3.826, 3.841 and 3.859 m. Non sticky, very slightly plastic; abrupt, smooth.
3.859-4.050	Sandy, silty clay gyttja with many fine to medium bands (0.5 to 25.0 mm thick) from 5Y 4/2 olive gray (moist), 5Y 5.5/2 olive gray (dry) to 5Y 3/2 dark olive gray (moist), 5Y 5.5/3 olive (dry); distinctive laminae (<0.5 mm thick) with abundant Cladocera remains at 3.941, 3.964, 4.009 and 4.015 m. Non sticky, very slightly plastic; abrupt, smooth.
4.050-4.235	Sandy, silty clay-gyttja with many fine to medium bands (1.0 to 15.0 mm thick) ranging from 5Y 4/2 olive gray (moist), 5Y 5.5/2 olive gray (dry) to 5Y 3/2 dark olive gray (moist), 5Y 5.5/3 olive (dry). Laminae at 4.148 to 4.146 and 4.208 to 4.206 m consist primarily of redeposited Mazama tephra grading from fine sand to silt; charcoal-rich laminae with redeposited Mazama tephra grading from fine sand to silt occur at 4.058 to 4.050 and 4.190 to 4.185 m. Nonsticky, slightly plastic; abrupt, smooth.
4.235-4.610	Redeposited, silt size Mazama tephra with distorted laminae of alternating finer and coarser tephra, 5Y 7/1.5 light gray (moist), 5Y 8/1 white (dry). Nonsticky, non plastic.

Age and Analyses

Though reason, funding and absence of an independent fire-scar chronology dictated otherwise, I have established the age of the deposits and determined their potential for providing information on past environmental conditions at

Blue Lake. Age was determined by radiocarbon dating and by probable correlation of volcanic ashes (tephrochronology). Relative frequency of pollen, spores and algae suggest significant differences in terrestrial vegetation and water quality over the past 6000 years. Layers of charcoal and charred plant debris attest to past fires and past vegetation.

Replicate samples (with volumes of 2.3 cm^3) from 10 levels furnished sediments for determination of weight loss on ignition (Dean 1974), and for evaluating abundance and preservation of fossil pollen, spores and algae. Pollen was extracted routinely. Sample dry weight was determined after drying at 105°C for >24 hours; then, weight loss after combustion at 600° and 950°C gave estimates of organic and carbonate carbon content (Table 3). Samples of whole core or wood were pretreated with NaOH and HCl to remove humates and carbonates before combustion for radiocarbon dating at Washington State University (Table 4). Percent of major elements in glass shards--as determined by electron microprobe in the Department of Geology, Washington State University (Table 5)--characterize three volcanic ash layers and suggest correlation with tephra from lake cores on Steens Mountain to the north.

Table 3. Organic and carbonate carbon content, as percent dry weight, of sediments from cores, Blue Lake, Pine Forest Range, Nevada.

Depth (meters)	Percent Dry Weight	
	Organic	Carbonate
0.005	25.41%	2.43%
0.015	25.62	2.38
0.350	19.92	2.80
1.600	22.54	2.60
2.150	11.05	3.04
2.320	20.00	2.39
2.950	17.18	2.25
3.100	20.73	2.52
3.650	17.54	2.26
4.200	6.35	0.85



Figure 2. Coring Blue Lake, Pine Forest Range, Nevada (July 1986). The 2 m-long core with a 10 cm-diameter was raised from beneath 14.5 meters of water.

BLUE LAKE CORES, PINE FOREST RANGE, NEVADA

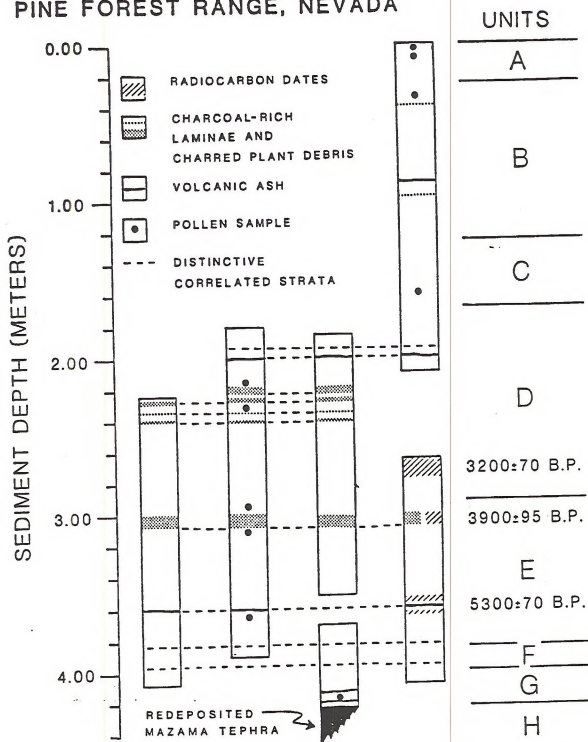


Figure 3. Radiocarbon dates, tephra, charcoal layers, stratigraphic units and correlation of cores from Blue Lake.

I selected three radiocarbon samples to estimate ages of the first tephra above Mazama ash and the thickest charcoal-rich layer. Dates of 5300 and 3900 B.P. and an overlying date of 3200 B.P. are in proper stratigraphic sequence. In addition, major element composition of the tephra at 1.992 and 0.875 meters are close to those of tephra III (about 2850 B.P.) and Tephra I (about 1150 B.P.) of the Steens Mountain sequence.

The volcanic ash at 3.606 meters was lighter in color than underlying beds of redeposited Mazama tephra. Microprobe analyses, however, indicate two and perhaps three groups of chemically distinct glass shards. The first of these [Table 5, 3.606(a)] is redeposited Mazama tephra, whereas the other two are from unknown sources. It is likely that the Mazama and another tephra (b) are mixed with an airfall volcanic ash from an unknown eruptive event (c) dating to about 5300 B.P. Further microprobe and mineralogical analyses will be required to reveal the sources of these ashes.

Table 4. Radiocarbon dates and tree ring corrected ages, Blue Lake, Pine Forest Range, Nevada, and Upper Cow Lake, Jordan Craters, Oregon.

Sediment Depth (meters)	Laboratory Number	Radiocarbon Date (B.P.)	Tree-ring Corrected Age (B.C.)	Material Dated
Blue Lake				
2.78 -2.68	WSU-3567	3200 $\pm$ 70	1485 $\pm$ 75	lake sediment
3.10	WSU-3566	3900 $\pm$ 95	2405 $\pm$ 145	charred wood
3.656-3.556	WSU-3568	5300 $\pm$ 70	4145 $\pm$ 105	lake sediment
Upper Cow Lake				
4.43-4.33	WSU-1234	3150 $\pm$ 350	1500 $\pm$ 500	charred wood

Blue Lake cores hold evidence for unusual fire regimes from about 4000 to 3000 B.P. when several layers of charred plant debris, accompanying graded beds of sand to clayey silt, suggest intense duff-destroying fires, and

subsequent erosion and transport to Blue Lake. Since that time only two fires left traces as charcoal-rich laminae (Figure 3). It seems likely that denser or different vegetation--not necessarily dominated by whitebark pine--growing under more moist conditions would have been required to carry the fires and produce such charcoal-rich deposits. But, how did the coarse sediments along with perfectly preserved and delicate plant remains come to be deposited in the middle of Blue Lake? Some combination of three possibilities occurs to me:

1. Blue Lake was shallower than now with the present center of the lake closer to shore; this seems unlikely, however, if moisture regimes actually contributed to a far greater than present fuel supply. Perhaps these fires date from a generally moist episode punctuated by droughts and conflagrations.
2. Melting snow or spring rain washed sediments onto ice that later drifted over the lake releasing its contents as it melted.
3. Winds accompanying a fire storm distributed charred plant parts across the lake.

The set of four charcoal layers dating from about 3000 B.P. (2.38 to 2.18 m sediment depth, Figure 3) is particularly interesting. High elevation cold conditions with sparse fuels typify whitebark pine stands of the northern Rocky Mountains where fires are infrequent. Depending on the site these stands have mean fire frequencies of 50 to 300 years (Arno 1986). Widespread fires in whitebark pines would only be expected with severe burning conditions. Because the Blue Lake forests are now even more sparse than most whitebark pine stands in the northern Rockies, large fires should be infrequent; according to these studies they have been. Perhaps, under a more moist climate regime about 3000 B.P., an episode of drought and an initial

fire storm in dense whitebark pine created fuel that fed repeated burns similar to those reported by Wellner (1970).

Whatever their means of deposition, such charcoal layers have not been deposited in Blue Lake for 3000 radiocarbon years and these deposits are extraordinary in their contents of charred, yet well preserved leaves, twigs and fruit. For example, cursory examination of the 4400-year old, 8-cm thick layer near 3-meters sediment depth (Tables 2, 4), revealed complete fascicles of a 5-needled pine, numerous whole leaves and fruit of Cercocarpus ledifolius, leaf bases of Ceanothus velutinus, twigs of Populus tremuloides, and remains of other species as well.

Widely varying ratios of sagebrush/pine (0.75 to 1.5) and sagebrush/grass pollen (2 to 10) in ten test samples suggest significant differences in the vegetation cover of the Pine Forest Range over the past 6000 radiocarbon years. Abundance of pine pollen at 4.20 meters, directly above Mazama tephra, indicates that pines occurred near the lake at that time. Even greater relative differences in the abundance of Isoetes microspores, Pediastrum colonies, layers of sponge spicules and Cladocera remains (Table 2) suggest that water quality, and perhaps water depth, has also varied considerably.

Carbonate content of the sediments (Table 3), however, shows little variation and no apparent trends as might be expected with prolonged periods of high evaporation and no overflow, or might result from episodes when carbonate-rich wind-born playa dust reached Blue Lake in unusual abundance. Recent bottom sediments of Blue Lake contain about 25% organic carbon by weight. All samples with <20% organic carbon are from levels that contain unusual amounts of sand or silt either as volcanic ash or deposits washed-in following fires. Excepting these events, Blue Lake has produced relatively organic rich sediments since shortly after the fall of Mazama tephra.

Table 5. Weight percent of major elements, as determined by electron microprobe analyses, of glass shards of volcanic ashes from sediments of Blue Lake, Pine Forest Range, Nevada.

Oxide	Weight % by Sample Depth (meters)				
	0.875	1.992	3.606(a)	3.606(b)	3.606(c)
Na ₂ O	3.35±0.24%	3.68±0.20%	4.70±0.11%	4.09±0.08%	2.43±0.91%
Fe ₂ O ₃	0.95±0.14	1.44±0.10	2.57±0.18	1.75±0.34	1.72±0.91
K ₂ O	3.87±0.26	3.82±0.12	2.68±0.10	3.30±0.04	5.95±1.06
MgO	0.16±0.05	0.17±0.03	0.47±0.06	0.20±0.05	0.10±0.06
CaO	0.80±0.17	0.91±0.11	1.66±0.08	1.02±0.11	0.52±0.42
Al ₂ O ₃	12.21±0.28	12.86±0.21	14.71±0.14	13.55±0.22	12.55±0.93
TiO ₂	0.15±0.06	0.19±0.03	0.38±0.04	0.18±0.07	0.15±0.08
SiO ₂	78.41±0.56	76.81±0.45	72.67±0.32	75.77±0.83	76.49±0.93
Cl	0.10±0.02	0.12±0.03	0.14±0.07	0.14±0.02	0.10±0.04
TOTAL	100.00	100.00	100.00	100.00	100.00

Discussion

To better understand the history of Blue Lake and its surrounding forest of whitebark and limber pines the youngest ashes should first be radiocarbon dated. If the dates confirm their major element correlation with Steens Mountain Tephra I and III, precise comparisons of fossil records from a forested and a steppe covered mountain might reveal unsuspected aspects of their vegetation histories. Though they would undoubtedly be productive, further studies of fossil pollen, spores, algae and macrofossils from the layers of charred plant debris are beyond the scope of this project. For now it seems certain that pines were important in the vegetation surrounding Blue Lake since at least 6000 B.P.

I had hoped to core through Mazama ash, case the hole, and continue down to the first sediments deposited after retreat of the Blue Lake glacier. Although, under ideal conditions and sufficient time, this could have been accomplished from our coring raft, it would be considerably simpler to core from the ice in winter.

There is much to be learned about the chronology of environmental changes of the last 6000 radiocarbon years from the cores already collected. Yet, the initial history of post glacial migration of whitebark and limber pines, and their associates, still lies buried in yesterday's mud beneath an unknown, but more than 40-cm, thickness of Mazama ash. Given relative depositional sequences in other lakes of the interior Pacific Northwest and northern Great Basin, I suspect that glacial till would be encountered within 2 meters below the primary airfall Mazama tephra.

Upper Cow Lake, Jordan Craters, Oregon

Introduction

Though not included in the proposal, Upper Cow Lake was cored at the request of BLM personnel of the Vale District. They hoped that it might hold a record of past environments or perhaps reveal the age of the lava flow that blocked Cow Creek to form the lake. In either case the information would be of direct value in the management and interpretation of the Jordan Craters Research Natural Area.

On July 24, 1986, we anchored our raft near the lower end of Upper Cow Lake in about 3.75 m of water (Figures 4, 5). After four days, we had raised several complete sets of overlapping cores. These penetrated through about 4.50 m of lake deposits composed of an apparently uniform sticky, gray clayey silt. The final drive of each core ended in stream gravels deposited just before Upper Cow Lake was formed by the plug of basalt flowing up the Cow Creek drainage.

Age

Upon opening a few cores at Washington State University I realized that-- short of freezing which would have rendered the cores unreliable for paleomagnetic measurements--there was no way to remove the core barrels without distorting the unusually sticky sediments. Also, their light gray color would make it difficult to locate the thin layers of volcanic ashes that were expected, but not recognized. Therefore, only one of the basal core drives was opened in the hope that organic matter associated with initial lake deposits would give their radiocarbon age. This single core held a charred twig, baked earth and dispersed, fragile sand-size charcoal detritus at the stream gravel to lake sediment contact.

The charred twig, that appeared to be in upright growth position, yielded only 0.4346 grams of charcoal after routine pretreatment (HCl and NaOH) for radiocarbon dating. Because the sample was small the standard deviation on its ^{14}C age is quite large (Table 4). Nonetheless, the Jordan Craters flow probably blocked the canyon of Cow Creek between 2800 and 3500 B.P.

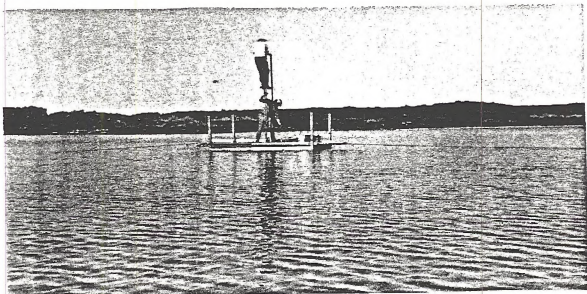


Figure 3. Coring at the lower end of Upper Cow Lake, Jordan Craters, Oregon (July 1986), near the basalt flow that--according to these studies--dammed the canyon of Cow Creek to form the Lake about 3150 B.P.



Figure 4. Upper Cow Lake, Jordan Craters, Oregon (1986). Robert R. Kindschy (Vale District BLM) contemplates secrets of the past and mysteries of the present on a fun-filled Sunday afternoon in July.

Discussion

Two or three more basal sections of cores already collected should also yield charcoal that may date more precisely the event that dammed Upper Cow Lake and produced the spectacular volcanic terrane of Jordan Craters Research Natural Area. Before more cores are opened, however, we must x-ray at least one complete overlapping section. X-rays will reveal differences in texture and the potential position of tephra obscured by the uniform appearing grey clayey silt. In the meantime unopened core barrels full of sediments from Upper Cow Lake have been placed in cold storage. They will remain available for study for at least another year.

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